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The Limnological status of Lake Mead and Lake Mohave under present and future powerplant operations of Hoover Dam

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LAKE MEAD LIMNOLOGICAL RESEARCH CENTER

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Technical Report No. 1

TECHNICAL REPORT SERIES

OVERTON

ECHO BAY

LAS VEGAS

LAS VEGAS BAY

VIRGIN BASIN

COLORADO RIVER

BOULDER BASIN

GREGG BASIN

HOOVER DAM

DEPARTMENT OF BIOLOGICAL SCIENCES

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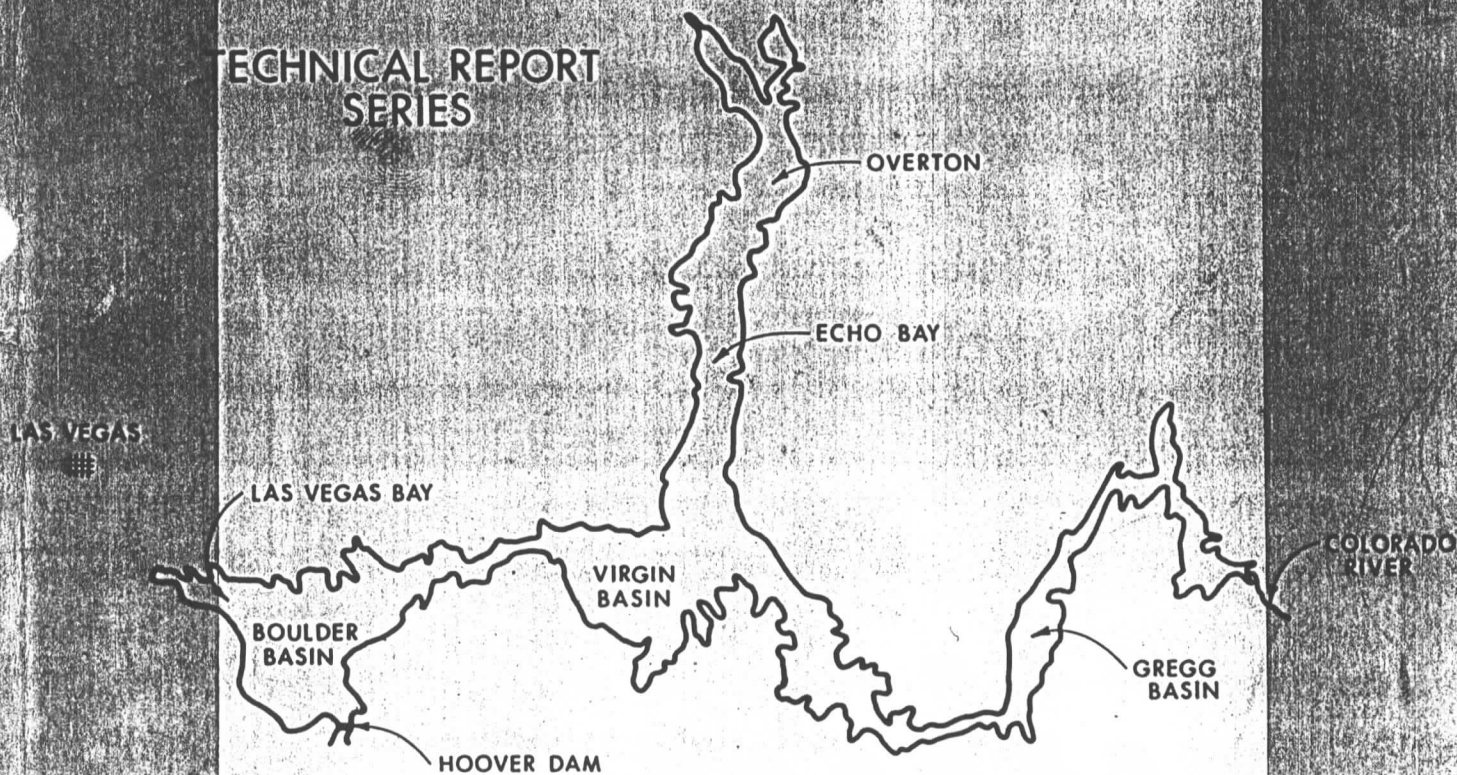
LAS VEGAS

THE LIMNOLOGICAL STATUS OF LAKE MEAD
AND LAKE MOHAVE UNDER PRESENT AND FUTURE
POWERPLANT OPERATIONS OF HOOVER DAM

Larry J. Paulson, John R. Baker and James E. Deacon

Lake Mead Limnological Research Center
University Of Nevada, Las Vegas
Technical Report NO. 1

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES, continued

LIST OF FIGURES, continued

LIST OF FIGURES, continued

LIST OF TABLES

ACKNOWLEDGEMENTS

A) The U.S. Bureau of Reclamation is considering several alternatives for modifying Hoover Dam to increase peak-power output. Each alternative will require a peak discharge in excess of current levels $(25-30,000 \text{ ft.}^3 \cdot \text{sec.}^{-1})$.

B) Investigations were conducted on Lake Mead and Lake Mohave to assess the impacts of these power modifications on the limnology of the reservoirs.

C) Physical (temperature, oxygen, pH, conductivity, and light), chemical (nitrogen and phosphorus) and biological (chlorophyll-a, phytoplankton productivity, and phytoplankton and zooplankton species composition) measurements were made monthly at 15 reservoir stations in Lake Mead and 5 in Lake Mohave. Nutrients were also measured monthly in the Colorado River at Pierce Ferry and below Hoover Dam and in Las Vegas Wash.

D) Inflow from the Colorado River formed a density current in Lake Mead and Lake Mohave that varied seasonally in relation to temperature. In Lake Mead, the river formed an underflow in the winter, an overflow in the spring and a shallow and deep interflow in the summer and fall. In Lake Mohave, inflow from Hoover Dam formed an underflow during the spring, summer and fall, but mixed completely in uplake areas during the winter.

E) Inflow from Las Vegas Wash also formed a density current in Las Vegas Bay. The density current flowed along the bottom in the inner bay for most of the year and in the middle bay during the winter. This changed to an interflow in the summer and fall as the density

current flowed along the thermocline in the middle bay.

F) The Colorado River provided 80% of the inorganic nitrogen, but Las Vegas Wash contributed 70% of the inorganic phosphorus to Lake Mead. The Upper Basin was phosphorus-limited and the Lower Basin was nitrogen-limited during the summer. Equal proportions of inorganic nitrogen and phosphorus (42%) were retained in the Upper Basin of Lake Mead, but nitrogen retention decreased to 7% and phosphorus to 33% in the Lower Basin. Input of nitrogen to the Lower Basin from Boulder Canyon occurred primarily below the euphotic zone. This, and high nitrate loss from Hoover Dam, greatly reduced nitrogen retention in the Lower Basin.

G) Nitrogen and phosphorus loss from the hypolimnion discharge at Hoover Dam provided the primary nutrient input to Lake Mohave. Mixing of river-and reservoir-water resulted in high productivity in Eldorado Canyon of Lake Mohave. Inorganic nitrogen and phosphorus retention averaged 37% and 31% respectively. However, retention of total nitrogen and phosphorus was low due to rapid flushing of the reservoir.

H) The Upper Basin of Lake Mead was oligotrophic, Boulder Basin was oligotrophic-mesotrophic, and Las Vegas Bay and Lake Mohave were mesotrophic on the basis of average annual chlorophyll-a concentration. High nutrient loss from Hoover Dam is the principal reason for the low productivity in Lake Mead. However, this enriches Lake Mohave causing it to be more productive.

I) Reduced phosphorus loading from Las Vegas Wash with operation of the Advanced Wastewater Treatment plant will reduce the phosphorus

concentration and trophic state in most of the Lower Basin and Lake
Mohave. However, areas in the inner Las Vegas Bay will still receive
sufficient phosphorus to stimulate phytoplankton growth.

J) Upgrading of existing generating units or addition of new units will
require an increase in peak-discharge to 49,000 and 56,000 $ft.^3 \cdot sec.^{-1}$
and minimum flows of 2000 $ft.^3 \cdot sec.^{-1}$. Alternating high and low
discharge will cause an oscillation of the thermocline in Black Canyon,
near the dam. This will increase mixing rates and cause a slight
increase in productivity in that area. However, these changes will
not be perceptible without the aid of limnological monitoring equip-
ment. At low lake elevations (ca. 1100 ft.), it is probable that
slightly warmer water will be pulled to the lower intake gates
(900 ft.) on a peak-power cycle and increase the temperature of the
discharge by 1-2°C. Operation from the upper intake gates (1045 ft.)
at low lake elevations could increase the temperature of the discharge
by 5-8°C.

The alternating high and low discharge will have the greatest impact
on Lake Mohave. The interface between river-and reservoir-water
will shift down-lake and thermal stratification will be disrupted
under high discharge. At low discharge, the interface will move
up-lake and extend into the river section of Black Canyon. This
could extend to Willow Beach if lake elevations exceed 630 ft. and
discharge drops below 2000 $ft.^3 \cdot sec.^{-1}$.

K) Operation of a pump-storage unit at Hoover Dam will require a peak-
discharge of 76,000 $ft.^3 \cdot sec.^{-1}$, periods of no flow and reverse flows
of 25,000 $ft.^3 \cdot sec.^{-1}$. The turbulence generated by prolonged operation
of a pump-storage unit will eventually disrupt thermal stratification

in Black Canyon of Lake Mead. This will decrease the temperature

of surface water and increase that in the discharge. On a pumping

cycle, warm water will be drawn to Hoover Dam which will cause

considerable fluctuation in temperature of the river. This,

interspersed with periods of no flow, will create problems for

recreational use and fisheries in Black Canyon between Hoover

Dam and Willow Beach.

1.0 INTRODUCTION

The ever-increasing demand for energy in the southwest has led to a search for additional sources of power generation. Coal-fired powerplants currently provide most of the baseline energy in the southwest, but this must be supplemented with hydroelectric power during periods of peak demand. In order to provide additional peaking power, the U.S. Bureau of Reclamation is considering a number of projects to modify existing hydroelectric facilities, or add new facilities in the Lake Mead Recreation Area.

The Hoover Powerplant Modification Feasibility Investigation was authorized by Congress on December 16, 1975 to determine the feasibility of: (i) adding one or more hydroelectric generating units to Hoover Dam, (ii) adding one or more reverse turbine pump-storage units to Hoover Dam, and (iii) upgrading the existing generating units for greater capacity (USDI 1978). In addition, offline pump-storage systems are currently being considered for installation in three locations in Lake Mead and one location in Lake Mohave (USDI 1977).

The feasibility of these projects, in part, depends upon the impact to recreational and other beneficial uses of the reservoirs and the river. A primary concern is that these projects could significantly alter the physical, chemical, and biological properties of the reservoirs. Therefore, the U.S. Bureau of Reclamation initiated this study to determine: (i) the current limnological status of Lake Mead and Lake Mohave, (ii) the relationship between the physical, chemical and biologica: factors in Lake Mead and Lake Mohave, and (iii) the effect of the hydroelectric projects on the future limnological status of Lake Mead and Lake Mohave.

2.0 DESCRIPTION OF THE STUDY AREA

2.1 Lake Mead

Lake Mead is a large interstate impoundment located in the Mohave Desert of southeastern Nevada and northwestern Arizona 15 km northeast of Las Vegas, Nevada. The reservoir was formed in 1935 by construction of Hoover Dam (USDI 1966) and is the second in a series of reservoirs on the Colorado River that include Lake Powell, Lake Mead, Lake Mohave, and Lake Havasu. Lake Mead extends 183 km from the mouth of the Grand Canyon (Pierce Ferry) to Black Canyon, the site of Hoover Dam. The reservoir is 28 km wide between Bonelli Bay and Overton, the northwest arm of the reservoir (Fig. 2.1). Lake Mead is comprised of four large basins: Boulder, Virgin, Temple and Gregg Basin, interspersed with four narrow canyons: Black, Boulder, Virgin and Iceberg Canyon. The reservoir is bordered by the Muddy and Frenchman Mountains on the north and the Virgin and Black Mountains on the south. In this report, we refer to the area from Virgin Basin to Pierce Ferry as the Upper Arm; the area above Boulder Canyon as the Upper Basin, and the area below Boulder Canyon as the Lower Basin.

In terms of volume, Lake Mead is the largest reservoir in the country, and second only to Lake Powell in surface area (Table 2.1). The shoreline is extremely irregular (SLD = 9.7) and includes several large bays (Las Vegas and Bonelli) and numerous coves. The reservoir has a short hydraulic retention rate (3-4 yrs.) due to the great inflow from the Colorado River. The discharge from Hoover Dam is in the hypolimnion at 83 m depth (at operating level of 364 m). Other pertinent morphometric characteristics for Lake Mead are summarized in Table 2.1.

The principal water inflow to Lake Mead is derived from the Colorado River, but the Virgin and Muddy Rivers, which discharge into the Overton

MAP OF LAKE MEAD
Arizona — Nevada

Muddy River

Virgin River

Overton (53)

LEGEND

—————Thalweg of Colorado River

Shoreline Elevation 366 m

0   5 km

Arm

Echo Bay (45)

Overton

Grand Wash

Middle Las Vegas Bay (3)

Boulder Canyon (23)

Iceberg Canyon (80)

Las Vegas Wash

Pierce Ferry

(27) Virgin Basin

Temple Bar (64)

(73) South Cove

Inner Las Vegas Bay (2)

Outer Las Vegas Bay (10)

Boulder Basin (11)

Gregg Basin

Virgin Canyon

(18) Hoover Dam

Figure 2.1   Map of Lake Mead

Table 2.1   Morphometric characteristics of Lake Mead and Lake Mohave [derived from USDI (1966), Lara and Sanders (1970), Hoffman and Jonez (1973)].

Parameter	Lake Mead	Lake Mohave
Maximum operating level (m)	374.0	197.0
Maximum depth (m)	180.0	42.0
Mean depth (m)	55.0	19.5
Surface area (km^2)	660.0	115.0
Volume ($m^3 \times 10^9$)	36.0	2.3
Maximum length (km)	183.0	108.0
Maximum width (km)	28.0	6.4
Shoreline development*	9.7	3.0
Discharge depth (m)	83.0	42.0
Annual discharge (1977) ($m^3 \times 10^9$)	9.3	9.3
Replacement time at maximum operating level (years)	3.9	.24

* Unit less parameter to measure regularity of shoreline, value of 1 is equivalent to a lake shaped in a perfect circle.

4

Arm, and Las Vegas Wash, which discharges into Las Vegas Bay, also contribute year-round inflow. An approximate hydrologic budget for Lake Mead is presented in Table 2.2 to illustrate the relative inflow volume of these sources. There is only one principal water diversion from Lake Mead. This is located at the Southern Nevada Water Project, Saddle Island, where municipal, irrigation and industrial water are diverted to the Las Vegas Metropolitan Area.

The predominate geological feature of the Lake Mead floor and surrounding area is comprised of sedimentary deposits of the Muddy Creek formation that were formed during the Paleozoic and Mesozoic eras (Longwell 1936). These deposits consist of moderately consolidated sand, silt and clay. There are also layers of shale, sandstone and limestone interspersed with beds of gypsum, anhydrite and rock salt (Longwell 1936). Deposition of fine silt material since formation of the reservoir has altered the original floor of Lake Mead. Up to 25 m of silt material was deposited in the upper reaches of the reservoir before Lake Powell was formed in 1963 (Lara and Sanders 1970).

The vegetation surrounding Lake Mead is comprised primarily of salt cedar (Tamarix gallica) and creosote bush (Larrea tridentata). Emergent macrophytes are rare, but some coves contain a few isolated stands of cattails (Typha sp.) and sedges (Scirpus sp.). Submergent macrophytes are also rare, but Potomogeton pectinatus and Najas sp. occur sporadically in shallow coves.

The water quality of the Colorado River and Lake Mead is alkaline (pH 8.3) and the TDS averages about 700 $mg \cdot l^{-1}$ (Table 2.3). The principal constituents of TDS are the anions sulfate>carbonate>chloride and cations sodium>calcium>magnesium>potassium. Nitrogen concentrations are moderate (ca. 0.2-.5 $mg \cdot l^{-1}$) but phosphorus is extremely low (ca. .010 $mg \cdot l^{-1}$) throughout

Table 2.2 Hydrologic inputs and losses for Lake Mead (derived from USGS data from October 1975 - September 1976).

Input	Flow (m^3)	% of Total
Colorado River	1.077×10^{10}	98.0
Virgin River	11.2×10^{7}	1.0
Las Vegas Wash	7.23×10^{7}	0.60
Muddy River	$\underline{3.72 \times 10^{7}}$	$\underline{0.34}$
Total Input	1.099×10^{10}	100.0
Diversions	1.12×10^{8}	
Evaporation	1.16×10^{9}	
Discharge	$\underline{1.03 \times 10^{10}}$	
Total Output	1.27×10^{9}	

Table 2.3   Chemical characteristics of inflow and discharge for
            Lake Mead and Lake Mohave. (USGS data, average for
            October 1975 - September 1976).

Parameter	Grand Canyon Gage Station	Hoover Dam Gage Station	Davis Dam Gage Station
pH (std.)	8.0	7.7	8.0
Conductivity (μmho$\cdot$cm^{-2})	945	1086	1089
Total dissolved solids (mg$\cdot$l^{-1})	617	705	714
Calcium (mg$\cdot$l^{-1})	74	86	84
Magnesium (mg$\cdot$l^{-1})	26	28	29
Potassium (mg$\cdot$l^{-1})	4.1	4.9	5.0
Bicarbonate (mg$\cdot$l^{-1})	170	163	157
Sulfate (mg$\cdot$l^{-1})	228	283	293
Chloride (mg$\cdot$l^{-1})	79	85	87
Silica (mg$\cdot$l^{-1})	7.0	8.3	7.8
Nitrate (N) (mg$\cdot$l^{-1})	.50	.41	.28
Phosphate (P) (mg$\cdot$l^{-1})	.010	.013	--

the river. Silica is present in very high quantities (ca. 7-8 $mg \cdot l^{-1}$).

The climate is arid with annual precipitation averaging about 8 cm. Mean annual temperature is about 19°C with a range from 45°C in the summer down to -1°C in the winter. Winds are highly variable, but generally, southerly winds prevail in the summer compared to north-easterly winds in the winter.

2.2 Lake Mohave

Lake Mohave is located 120 km south of Las Vegas, Nevada. The western side of the reservoir is located in Nevada and the eastern side in Arizona. This reservoir was formed in 1950 by construction of Davis Dam and is the third mainstream reservoir on the Colorado River. Lake Mohave extends 108 km south from Hoover Dam to Davis Dam (Fig. 2.2). It is only 6.4 km wide and is best described as a "run of the river" reservoir. Lake Mohave has two small basins, Eldorado and Little Basin at the upper end, and Cottonwood Basin located in the middle of the reservoir. The reservoir is bordered by two discontinuous mountain ranges. The first 32 km, which are located in Black Canyon, are bordered by the Black Mountains to the east and the Eldorado Mountains to the west. The Black Mountains continue to parallel the east side of the reservoir, but the Eldorado Mountains join the Newberry Mountains on the west side near Davis Dam.

Lake Mohave is small in terms of volume and surface area by comparison with Lake Mead (Table 2.1). It also has a more regular shoreline (SLD=3.0) and contains few coves or bays. The hydraulic retention time for Lake Mohave is only .24 yr. due to rapid flushing by the Colorado River. The discharge at Davis Dam originates from the hypolimnion at 42 m depth.

The only significant inflow to Lake Mohave is from the Colorado River via discharge from Hoover Dam. The Willow Beach Trout Fish Hatchery, located 18 km downstream from Hoover Dam, discharges some water, but this

MAP OF
LAKE MOHAVE

HOOVER DAM

El Dorado
(4)

Cottonwood
Cove

Katherine Landing

DAVIS DAM (1)

Cottonwood
Basin
(2)

Willow
Beach

Monkey Hole (5)

Little Basin (3)

0   5 km
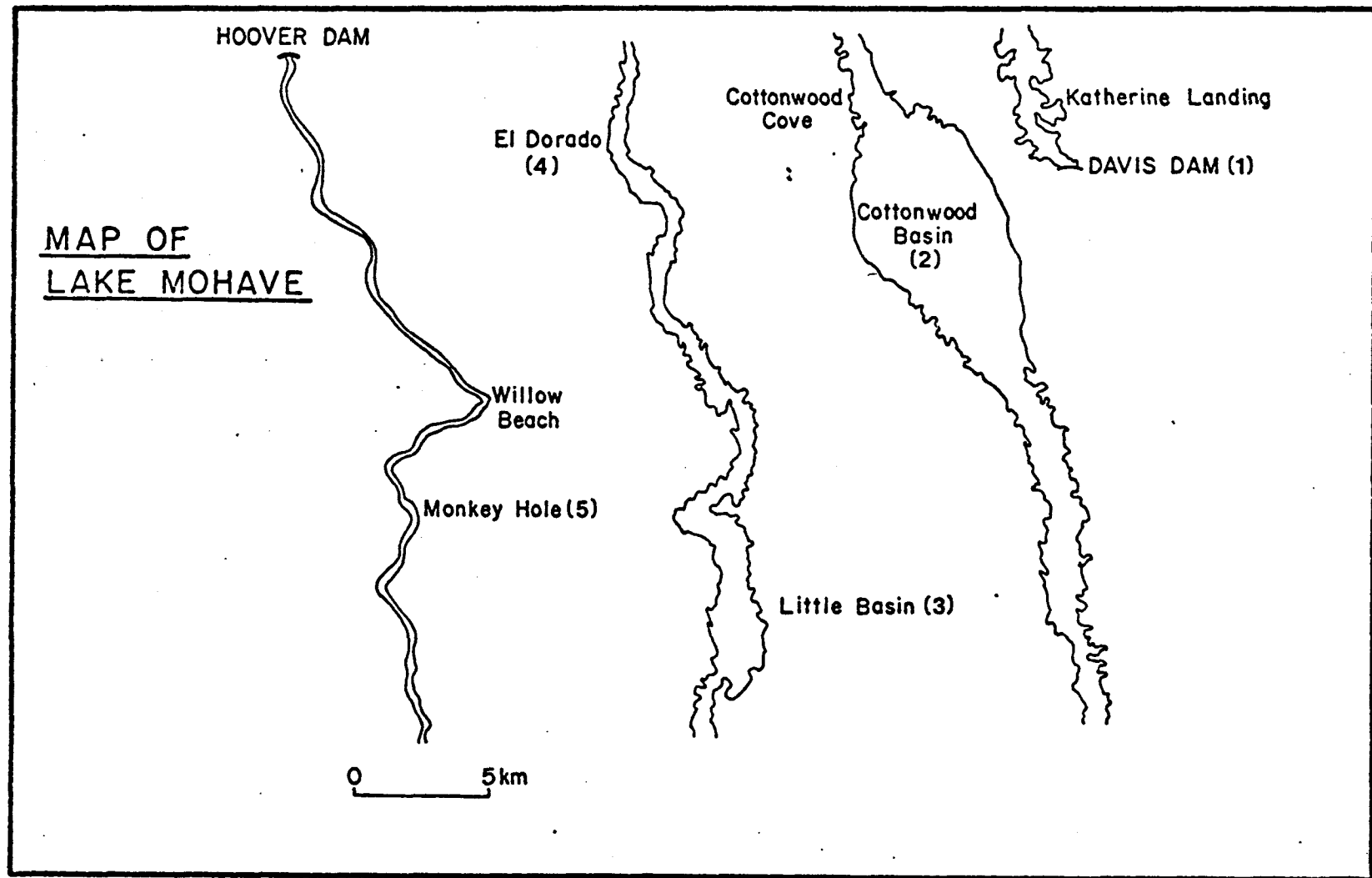
Figure 2.2   Map of Lake Mohave

is insignificant relative to the Colorado River. There are no major diversions of water from Lake Mohave.

The Lake Mohave floor is comprised primarily of clay, silt and sand deposits of the Chemheovis formation (Longwell 1936). Alluvial deposits brought in by runoff from the surrounding mountains also comprise a large portion of the bottom substrate. Although the upper reservoirs now trap most of the sediment from the Colorado River, Lake Mohave still contains remnant silt deposits from the Colorado River.

The vegetation around Lake Mohave is similar to Lake Mead, except that stands of mesquite (Prosopis odorata) and palo verdi (Cercidium sp.) are more common.

The water quality of Lake Mohave is also similar to Lake Mead except that there is a slight increase in TDS, and nitrate is reduced by approximately one-half in the reservoir (Table 2.3).

3.0 METHODS

3.1 Sampling Locations

The location of sampling stations in Lake Mead and Lake Mohave are depicted in Figs. 2.1 and 2.2. The stations are labeled by name and number for easy reference in subsequent sections of this report.

3.2 Phytoplankton Productivity

Phytoplankton productivity was measured monthly, in situ, with the ^{14}C-method (Steeman-Neilsen 1952, Goldman 1963). Water samples were collected from 0, 1, 3, 5, 7, 10 and 15 m with a 3-liter Van Dorn sampler and transferred to 125-ml glass-stoppered reagent bottles. A light and opaque bottle from each depth were innoculated with 1 ml of a .96 μCi·ml^{-1} NaH^{14}CO$_3$ solution. The bottles were resuspended at the depth of collection and incubated for a 3-4 hour period. Since several stations had to be

sampled each day, synoptic incubations were used for stations where light transmittance was similar. Stations 2, 3,10 (Las Vegas Bay), 53 (Overton) and 80 (Iceberg) were incubated on location. Stations 11 and 18 (Boulder Basin) were incubated at station 10; stations 23 (Boulder Canyon) and 27 (Virgin Basin) were incubated at station 45 (Echo Bay); and station 64 (Temple Bar) was incubated at station 73 (South Cove). After the incubation period, the bottles were stored in light-proof boxes and transported to the laboratory for processing.

The entire contents of each bottle were filtered through .45 μ membrane filters (47 mm dia.) at 100 mm Hg. The filters were rinsed with .005 N HCl to dissolve any carbonate residue embedded in the filters. Each filter was transferred to a 22 ml scintillation vial, allowed to dry, and then filled with 20 ml of scintillation cocktail (2 parts PCS:1 part Xylene). Radioactivity was measured with a Beckman LS-100 Scintillation Counter, calibrated with a certified standard $NaH^{14}CO_3$ solution.

In order to determine inorganic carbon (^{12}C), total alkalinity was determined on a water sample collected at the same depth as phytoplankton productivity. Temperature and pH were first measured, and a 50 ml sample was then titrated with .02 N HCl to pH 4.8 (APHA 1975). Inorganic carbon was calculated from conversion tables of Saunders, Trama and Backman (1962).

A pyroheliometer (Weather Master), placed in the vicinity of the sampling stations was used to record solar radiation during the incubation period. Incident solar radiation was determined by planimetry of the recording. Estimates of total daily solar radiation were obtained from the University of Nevada, Las Vegas Physics Department. Daily phytoplankton productivity was computed by extrapolation from the ratio of solar radiation during the day to solar radiation during the incubation period. Integral

(areal) phytoplankton productivity (mg $C \cdot m^{-2} \cdot day^{-1}$) was computed by trapezoidal integration of discrete depth interval measurements.

3.3 Chlorophyll-a

One-liter water samples were collected monthly from 0, 3, and 5 m at each station and pooled to form a composite sample. The samples were stored in the dark in an ice chest and immediately transported to the laboratory. A 500-1000 ml subsample, depending upon phytoplankton density, was treated with magnesium carbonate and filtered through glass fiber filters (GFC) at 100 mm Hg. The filters were then ground in 3-5 ml of 90% acetone and the final volume brought to 10 ml. This was followed by a three-hour extraction period in the dark (Golterman 1969). The sample was then centrifuged and the supernatant decanted into 1 cm cuvettes. Absorbance readings were made at 750 nm and 663 nm on a Coleman Model 620 Spectrophotometer. Chlorophyll-a concentration was calculated according to the equations of Strickland and Parsons (1968).

3.4 Phytoplankton Identification and Enumeration

A 125 ml subsample was taken from each integrated chlorophyll-a sample, preserved with Lugol's solution and stored in a refrigerator until processed for enumeration. A modified version of Edmondson's simplified method for phytoplankton enumeration was employed for the study (Vollenweider 1969). The samples were settled in cylindrical chambers for a minimum of 2 days before examination, and 100 ml of the supernatant was then carefully decanted off and discarded. The concentrated sample was then centrifuged at low RPM for a brief period to further concentrate the sample. The relative abundance of each species was determined by scanning twenty microscopic fields of each sample. Colonies and filaments were counted as one unit, except in the case of Dinobryon sp., where individual cells

were counted as one unit. The ultra-plankton (<15μ) were identified at 1000X magnification using oil immersion. Dominant organisms were defined as the taxon having the highest population in a collection. Organisms comprising 10% or more of the total numerical cell concentration were considered common. Phytoplankton samples collected in July and August, 1978 were sent to Dr. Gerald Prescott, University of Utah and Dr. Norma Lang, University of California, Davis, for assistance in identification.

3.5 Zooplankton Enumeration and Identification

Three replicate zooplankton samples were collected at each station with a Wisconsin plankton net (80μ mesh) in a vertical haul from 40 m, or from the bottom at shallower stations. The samples were preserved with 5% formaldehyde and stored at room temperature in polyethylene vials. Zooplankton species and abundance were determined on five replicate sub-samples (1 ml) counted in a Sedgewick-Rafter counting chamber. Zooplankton density ($\#m^{-3}$) was estimated by extrapolation from the actual volume sampled with the Wisconsin net.

3.6 Chemical Analysis

3.6.1 Sample Collection and Preservation

Water samples for chemical analysis were collected monthly, with a 3-liter van Dorn sampler at 0, 5, 10, 20, 30, 40, and 60 or 90 m. The samples were transferred to acid-rinsed, plastic bottles and placed in an ice chest immediately after collection. Samples for ammonia analysis were stored in a refrigerator and analyzed within a few hours of collection. Samples for nitrate, phosphate and total phosphorus were frozen and analyzed within 1-2 weeks after collection. Water samples collected for chemical analysis by the U.S. Environmental Protection Agency Land and Water Monitoring Division, Las Vegas, Nevada were preserved with

mercuric chloride and analyzed within 1-2 months after collection. This included all samples collected from October, 1976 to December, 1977.

3.6.2 Ammonia

Samples for ammonia analysis were filtered through glass fiber filters (GFC). A 50 ml subsample, or a suitable aliquot diluted to the range of sensitivity, was analyzed for ammonia with the phenol hypochlorite method according to the procedures of Solorzano (1969) as modified by Liddicoat et al. (1975). Absorbance readings were made at 640 nm in a 10-cm cuvette with a Perkin Elmer Model 55 Spectrophotometer.

Methods used for ammonia analysis by EPA are described by Mullins et al. (1975).

3.6.3 Nitrate

Samples for nitrate analysis were filtered through glass-fiber filters (GFC). A 50 ml subsample, or a suitable aliquot diluted to the range of sensitivity, was analyzed by the hydrazine reduction method first described by Mullin and Riley (1955) and later updated by Kamphake et al. (1967). Absorbance readings were made at 543 nm in a 5-cm cuvette with a Perkin Elmer Model 55 Spectrophotometer. Methods used for nitrate analysis by EPA are described by Mullins et al. (1975).

3.6.4 Phosphate and Total Phosphorus

Phosphate and total phosphorus were determined using the ascorbic acid method described by Strickland and Parsons (1968) and later modified by Goldman (1974) for better application on lakes with low phosphorus concentration. For total phosphorus, a 50 ml, unfiltered sample was treated by acid hydrolysis (10.8 N H_2SO_4) to release phosphorus from particulate and dissolved organic matter. For phosphate, a 50 ml sample was filtered through glass-fibre filters, prior to addition of other

reagents. Absorbance readings were made at 645 nm in a 10-cm cuvette with a Perkin Elmer Model 55 Spectrophotometer. Methods used for total phosphorus and dissolved phosphorus by EPA are described by Mullins et al. (1975).

3.7 Physical Measurements

Temperature, oxygen, pH and conductivity were measured with a Hydrolab Model 11A Water Quality Analyzer. Underwater light transmittance was measured with a Li-Cor Model L-192 Underwater Quantum Sensor or a Kahlsico Model 268WA310 Submarine Photometer.

4.0 RESULTS

4.1 Temperature Structure and Current Patterns in Lake Mead

Fall Period

In October, 1977 the Colorado River inflow was $4.73 \times 10^8 m^3$, and this was colder (15.5°C) than the epilimnion of Lake Mead (ca. 21°C) Fig. 4.1.1). A moderate convergence (interface) was set up near Iceberg Canyon where the river water flowed under the warmer lake water. Mixing at the convergence and entrainment of lake-water increased the temperature of the inflow to 17.5°C, and an interflow (mid-water) developed at South Cove that moved down-lake between the 17.5°C and 21.5°C isotherms (20-30 m). The river-inflow elevated the 21.5°C isotherm in the up-lake areas (Fig. 4.1.1), but there was little change across Virgin and Boulder Basin indicating that the inflow did not extend much beyond Temple Bar. Temperature isotherms above and below the interflow were also disrupted somewhat in up-lake areas (Fig. 4.1.1), apparently due to entrainment of lake-water bordering the main interflow.

The temperature structure in the Overton Arm (Fig. 4.1.2) was fairly stable in October, reflecting a lack of any significant currents. However,
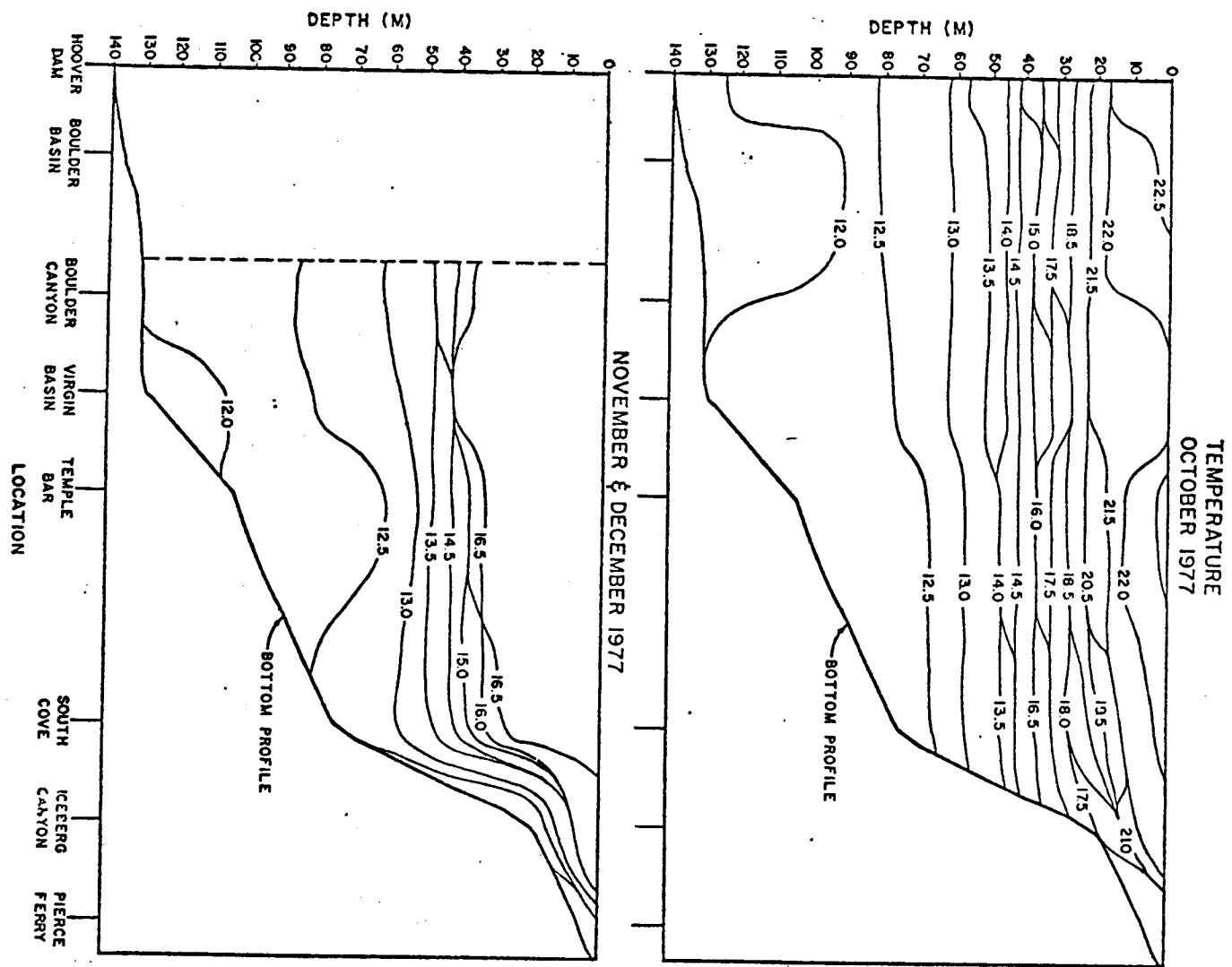
Figure 4.1.1 Temperature isotherms for Colorado River Channe
stations, Lake Mead in fall, 1977.
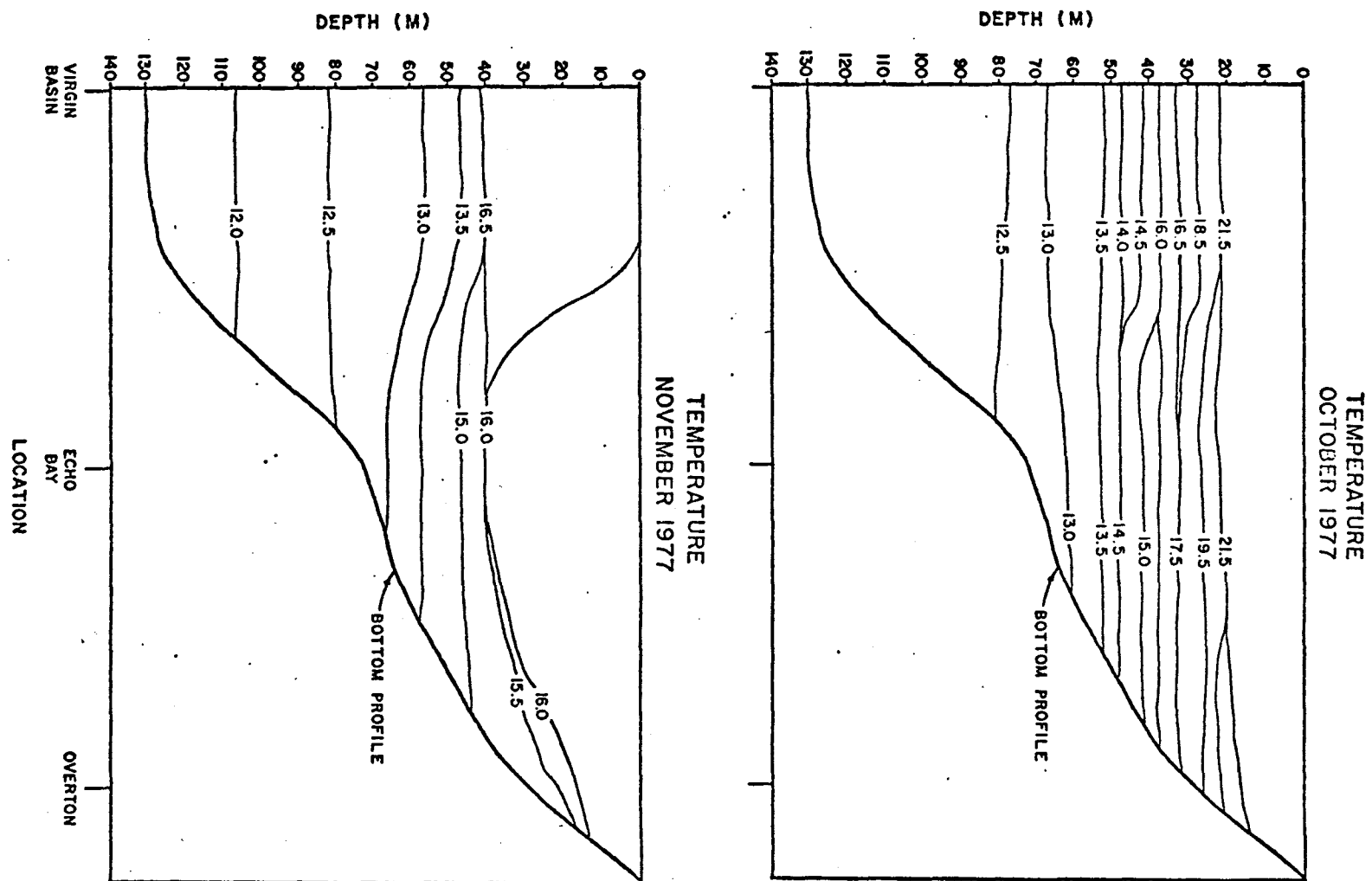
Figure 4.1.2 Temperature isotherms for Overton Arm stations, Lake Mead in fall, 1977.

the 12.5°C and 13.0°C isotherms were sloped down from Virgin Basin to Hoover Dam (Fig. 4.1.1). The 13.5°C isotherm was lower at Boulder Basin than in the Upper Arm and pulled down slightly at Hoover Dam. A lens of slightly cooler water (11.5°C) was located near the bottom in Boulder Basin (Fig. 4.1.3). The discharge from Hoover Dam was 5.3×10^8 m in October, and the slight changes in the temperature isotherms in Boulder Basin were probably caused by withdrawal currents from the dam.

The conductivity in Boulder Basin water was fairly uniform, but the high TDS inflow from Las Vegas Wash produced evident changes in conductivity in Las Vegas Bay (Fig. 4.1.4). Las Vegas Wash water entered Las Vegas Bay at a temperature of 19.5°C and a conductivity of 3400 μmhos·cm^{-1} in October. The volume was 6.24×10^6 m^3 and a density current was formed and flowed primarily along the bottom of the Inner Las Vegas Bay. This changed to an interflow between the Inner and Middle Las Vegas Bay. The main tongue of the density current (1250-1450 μmhos·cm^{-1}) flowed along the thermocline (20.5°-21.0°C) and extended past the Outer Las Vegas Bay into Boulder Basin. The conductivity in the inner and middle bay was slightly higher (1150 μmhos·cm^{-1}) than the outer bay or Boulder Basin due to mixing of the inflow.

Boulder Basin and Las Vegas Bay were sampled on 3-4 November compared to 29 November and 1 December for the Upper Arm. There was a considerable decrease in temperature between this period and therefore isotherms can only be constructed within each basin. The Colorado River inflow was 10.8×10^8 m^3 in November and 5.1×10^8 m^3 in December. The temperature of the river had decreased since October to between 9.7 and 0.5°C compared to 16.5°C for the epilimnion of Lake Mead (Fig. 4.1.1). The lake had not completely mixed, and a weak, unstable thermocline persisted

Figure 4.1.3   Temperature isotherms for Lower Basin stations, Lake Mead in fall, 1977.
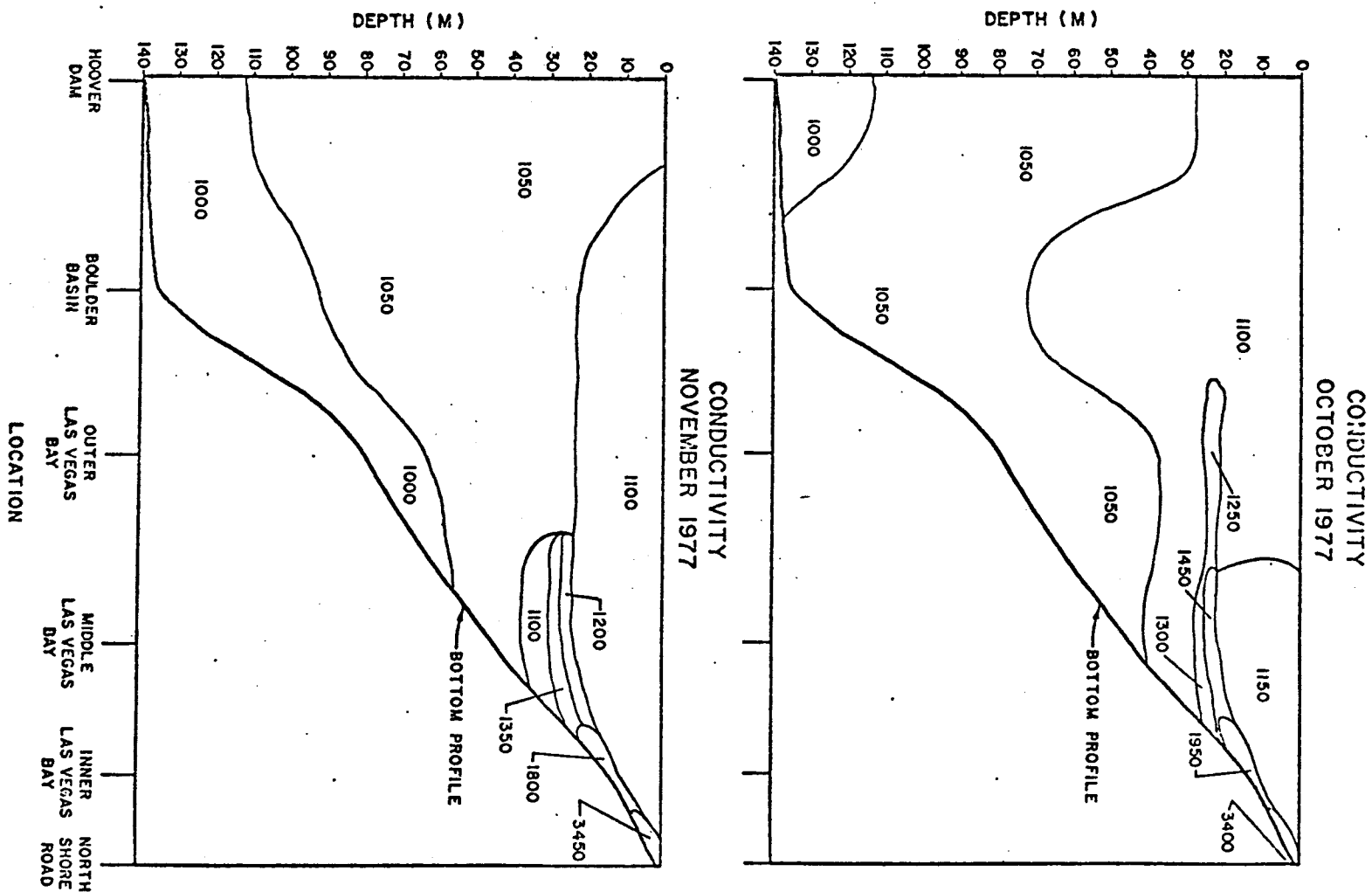
Figure 4.1.4   Conductivity isopleths for Lower Basin stations, Lake Mead in fall, 1977.

throughout the Upper Basin. A moderate convergence was formed in Iceberg Canyon where the cooler river-water flowed under lake-water. This increased the temperature of river-water slightly at Iceberg Canyon, and a deep interflow (35-45 m) developed at South Cove (Fig. 4.1.1). This significantly modified the temperature in up-lake areas. The 16.5°C isotherm was pushed down-lake at Iceberg Canyon and elevated slightly at South Cove and Temple Bar. The isotherms adjacent to the underflow (16.5°C) were sloped downward, parallel to the main underflow (11.5-12.0°C), from Iceberg Canyon to Temple Bar due to entrainment of lake-water. A part of the inflow may also have reached Virgin Basin, as indicated by the shape of the 13.5°C isotherm at that station.

The temperature in the Overton Arm was slightly cooler, and mixed to a greater depth, than Virgin Basin and the Upper Arm (Fig. 4.1.2). However, there was no evidence of significant current in the Overton Arm during the late fall.

In early November, the temperature in the epilimnion of Las Vegas Bay and Boulder Basin had decreased to 20.5°C, and the thermocline was located at 23 m (Fig. 4.1.3). The Las Vegas Wash inflow volume was 5.2 x $10^6 m^3$, and the temperature and conductivity were 14.1°C and 3450 $\mu mhos \cdot cm^{-1}$, respectively. . Las Vegas Wash inflow moved along the bottom of the Inner Las Vegas Bay but then formed an interflow between the inner and middle bay (Fig. 4.1.4). The thermocline was pushed down about 5 m at the middle bay but returned to a normal position between the middle and outer bay where the inflow mixed with lake water. Temperature isotherms were fairly uniform across Las Vegas Bay and Boulder Basin and there was very little change in conductivity beyond the outer bay. From October to November, the 12.0°C isotherm dropped from 90 m to 102 m in

Boulder Basin but then rose slightly at Hoover Dam. Discharge from Hoover Dam was 5.3×10^8 m for November, and this may have caused the shift in the 12.5°C isotherm as water was drawn to the dam. Beyond that, withdrawal currents did not appear to significantly influence circulation patterns in the Lower Basin in the late fall.

Winter Period

The transition between deep interflow and underflow occurred in late December. By January, 1978 lake temperature had decreased to between 12.0-13.0°C in the Upper Basin and to about 13.5°C in Boulder Basin (Fig. 4.1.5). The Colorado River had cooled to 7.0°C and discharge from Lake Powell had increased to $16.7 \times 10^8 m^3$. The high discharge pushed a wedge of cold river-water into Iceberg Canyon that displaced the 12.5-13.0°C isotherms down-lake. An underflow developed between Iceberg Canyon and South Cove where the cold inflow sank below lake-water. Mixing at the convergence and entrainment of lake-water increased the temperature of the inflow to approximately 11.5°C. The shape of the 11.5°C isotherm indicated that the underflow extended through Virgin Basin and possibly into Boulder Canyon.

By February, the river temperature had increased slightly (ca. 9.0°C), and the discharge had decreased to $7.6 \times 10^8 m^3$ (Fig. 4.1.5). The cold-water wedge present in up-lake areas in January subsided under this reduced flow and an underflow again developed at Iceberg Canyon. There was less entrainment of lake-water due to reduced flow, and therefore, colder water (11.0°C) flowed further down-lake than in January. However, the 12.5°C isotherm was located above Pierce Ferry in February indicating that surface water was pulled up-lake to replace that drawn down by entrainment with the river-inflow.
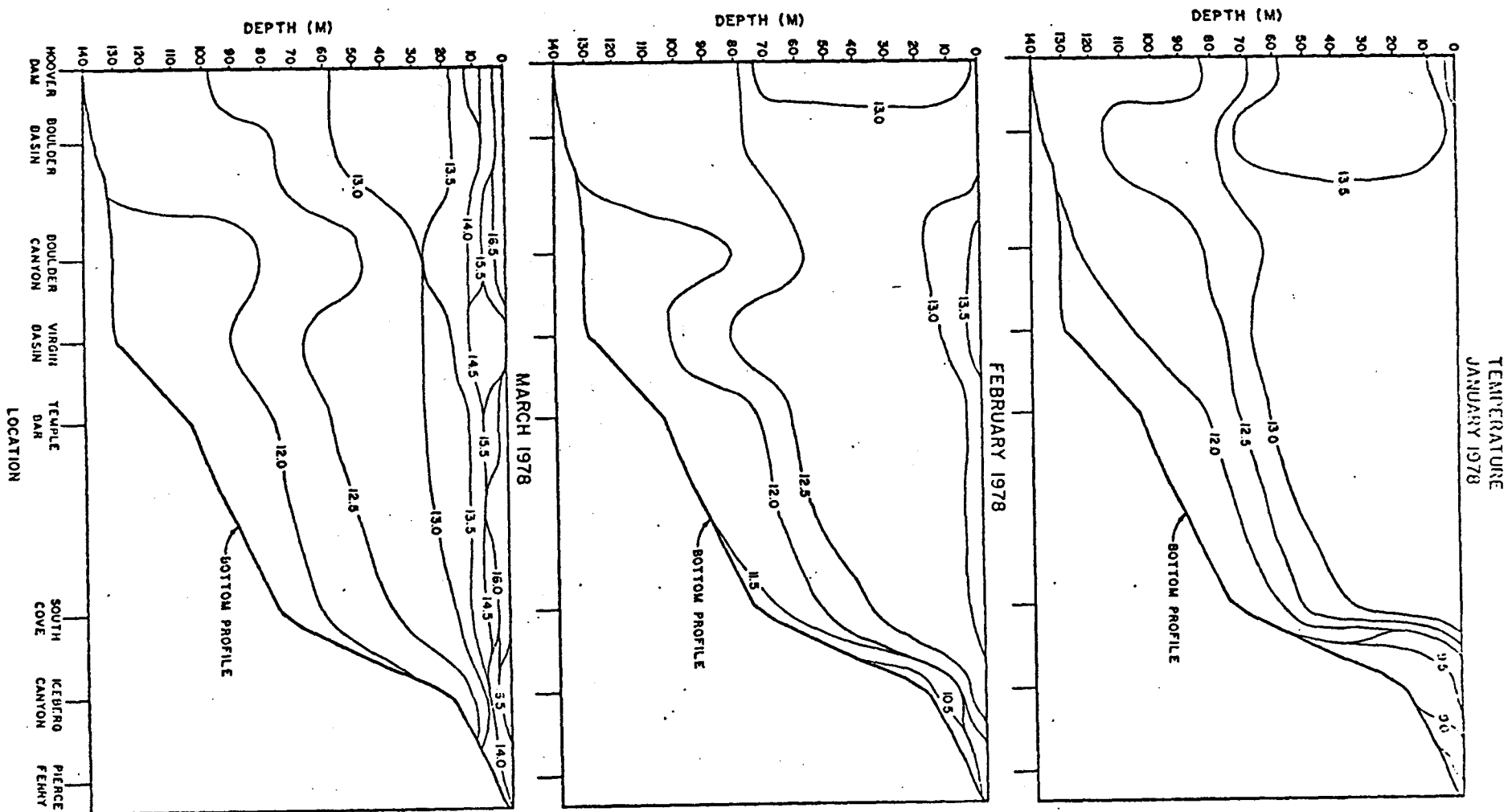
Figure 4.1.5 Temperature isotherms for Colorado River channel stations, Lake Mead in winter, 1978.

23

The 12.0°C and 12.5°C isotherms were sloped down in Virgin Basin but then elevated considerably at Boulder Canyon in February (Fig. 4.1.5). The same situation existed in March, except that now the 13.0°C and 13.5°C isotherms were also elevated at Boulder Canyon and sloped toward the surface and back up-lake throughout the Upper Basin (Fig. 4.1.5). The elevation of these isotherms at Boulder Canyon was probably due to a deep upwelling that occurred when the current was forced through the narrow canyon. However, this could also be a part of a large clockwise rotating circulation cell, of the type reported by Anderson and Pritchard (1951), that was set in motion from continual entrainment of surface water by the river-inflow during January and February.

The combined inflow volume of the Virgin and Muddy Rivers increased during the winter and totaled $19.9 \times 10^6 m^3$, $27.4 \times 10^6 m^3$ and $83.8 \times 10^6 m^3$, respectively, for January, February and March. The lake temperature in the Overton Arm during the winter was similar to the rest of Lake Mead (Fig. 4.1.6). The conductivity of these tributaries was equal to, or higher than, Las Vegas Wash in January and February but decreased in March with greater runoff (Fig. 4.1.7). The Virgin and Muddy River inflow formed a density current and flowed along the bottom in the Overton Arm during the winter. The density current extended to between Overton and Echo Bay in January and beyond Echo Bay in February and March. The density current may have extended into the Lower Overton Arm but was not detectable in Virgin Basin. Mixing of the Virgin and Muddy River inflow did not cause a significant increase in the conductivity of surface water of the Overton Arm during the winter. We did not observe density currents in the Overton Arm during the fall, spring or summer because the flow of the Virgin and Muddy River is greatly reduced by agricultural use.

Figure 4.1.6 Temperature isotherms for Overton Arm stations, Lake Mead in winter, 1978.
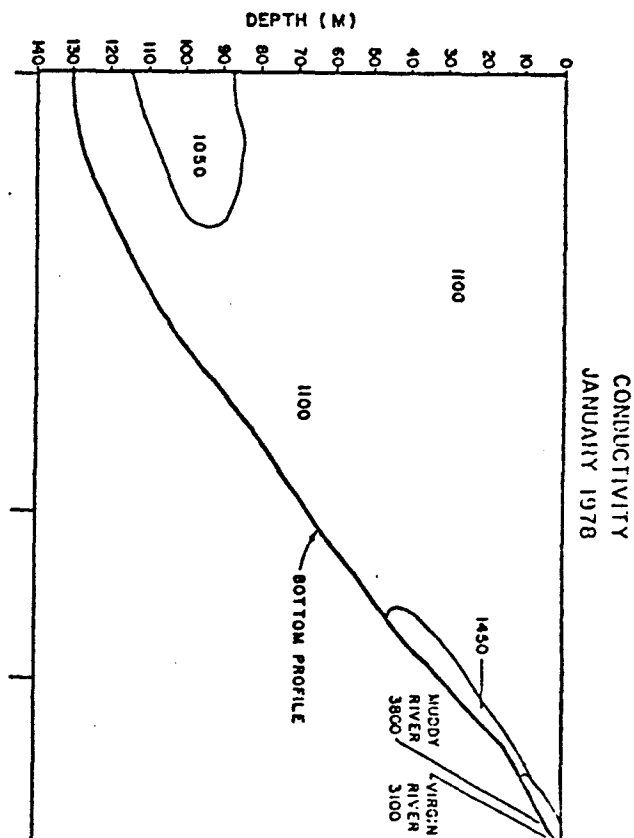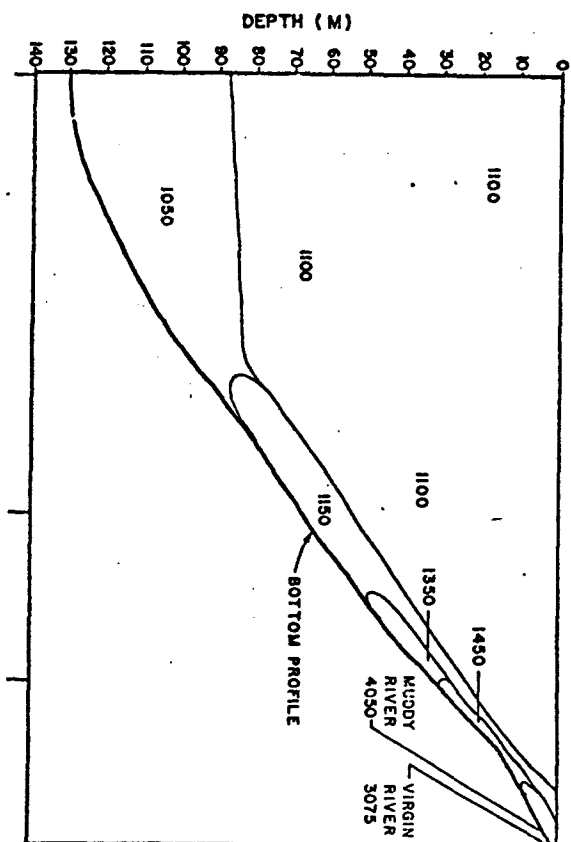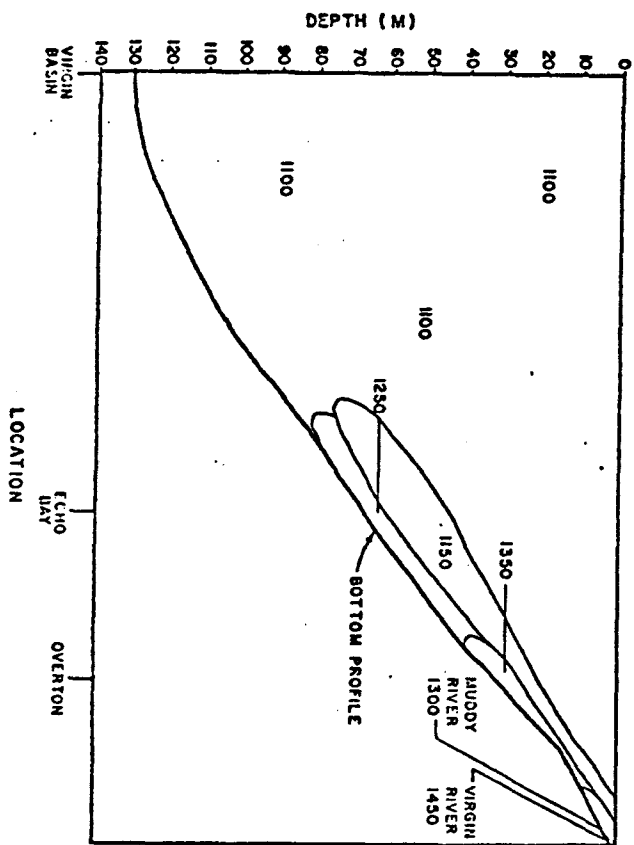
Figure 4.1.7   Conductivity isopleths for Overton Arm stations,
Lake Mead in winter, 1978.

The volume of Las Vegas Wash inflow increased to $7.3 \times 10^6 m^3$ and $7.4 \times 10^6 m^3$ for January and February. The temperature was 12.5°C for both months (Fig. 4.1.8), but the conductivity was slightly higher in February (3400 μmhos·cm^{-1}) than in January (3200 μmhos·cm^{-1}) (Fig. 4.1.9). The temperature of the Las Vegas Wash (Fig. 4.1.8) was nearly equal to the bay, but the high TDS of the inflow caused an underflow to develop throughout Las Vegas Bay (Fig. 4.1.9). The main tongue of the Las Vegas Wash density current was located within 2-3 m of the bottom and extended to between the Middle and Outer Las Vegas Bay. At that point, the density current appeared to spread laterally over the greater bottom area which reduced the velocity to the point where it dissipated due to vertical mixing. The conductivity in Las Vegas Bay was generally higher than the rest of Lake Mead in the winter, reflecting the continual mixing of high TDS inflow from Las Vegas Wash.

The temperature of Las Vegas Wash had increased to 18.5°C (Fig. 4.1.8) and the conductivity was 3800 μmhos·cm^{-1} by March (Fig. 4.1.9). The volume was $8.6 \times 10^6 m^3$. Although the temperature of Las Vegas Wash was warmer than Las Vegas Bay, the higher TDS caused Las Vegas Wash to underflow throughout the inner and middle bay. This produced a warm-water temperature tongue along the bottom of the inner and middle bay as slightly warmer Las Vegas Wash inflow was forced under colder lake-water. The density current again extended to between the Middle and Outer Las Vegas Bay. The conductivity in Las Vegas Bay and Boulder Basin (1150 μmhos·cm^{-1}) was higher than the Upper Basin (1050 μmhos·cm^{-1}) as a result of mixing of the Las Vegas Wash inflow and lake-water.

Spring Period

The temperature of the Colorado River increased to between 14.5°C and 15.0°C (Fig. 4.1.10), and the inflow volume was $5.1 \times 10^8 m^3$ in April.
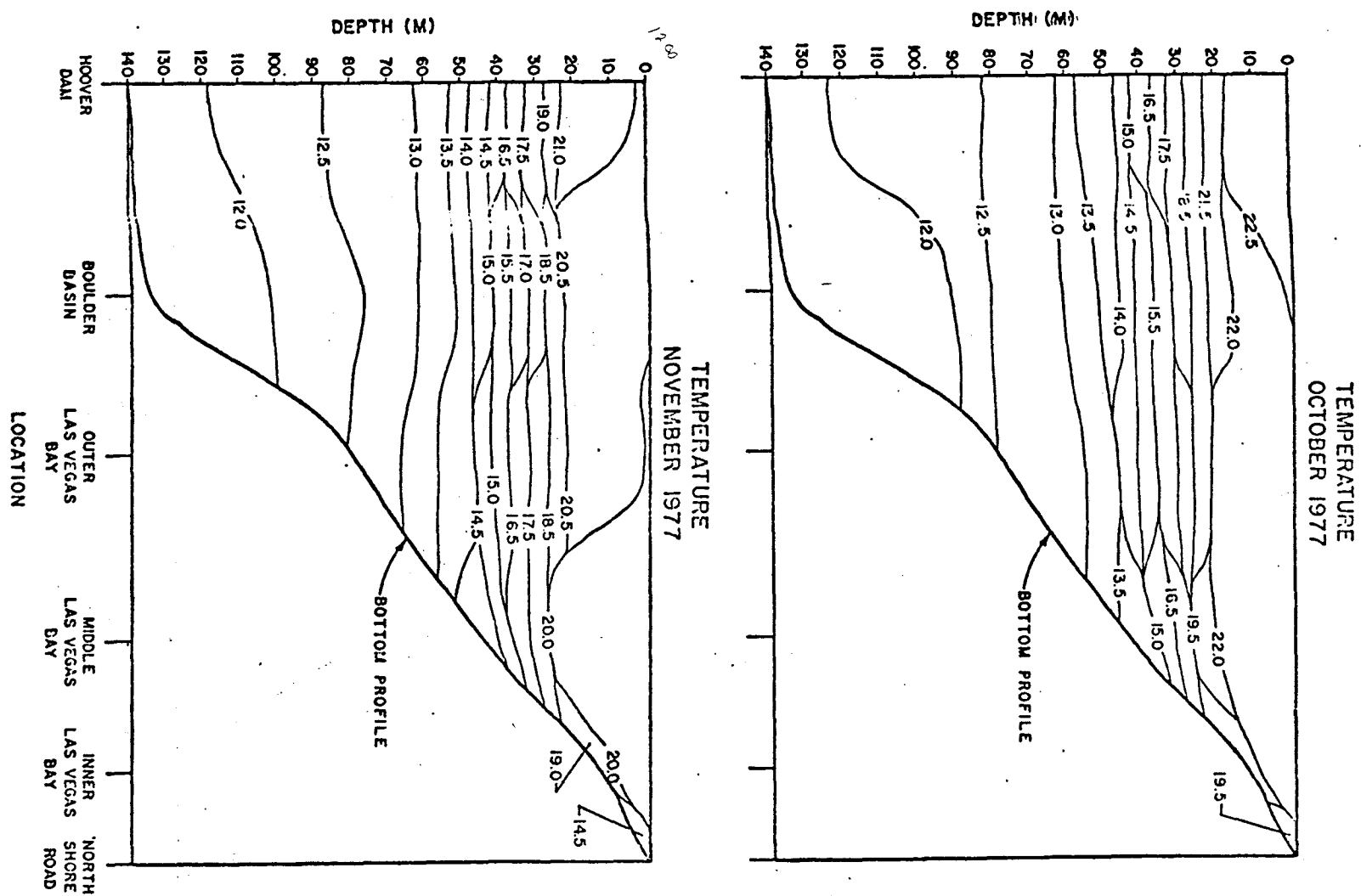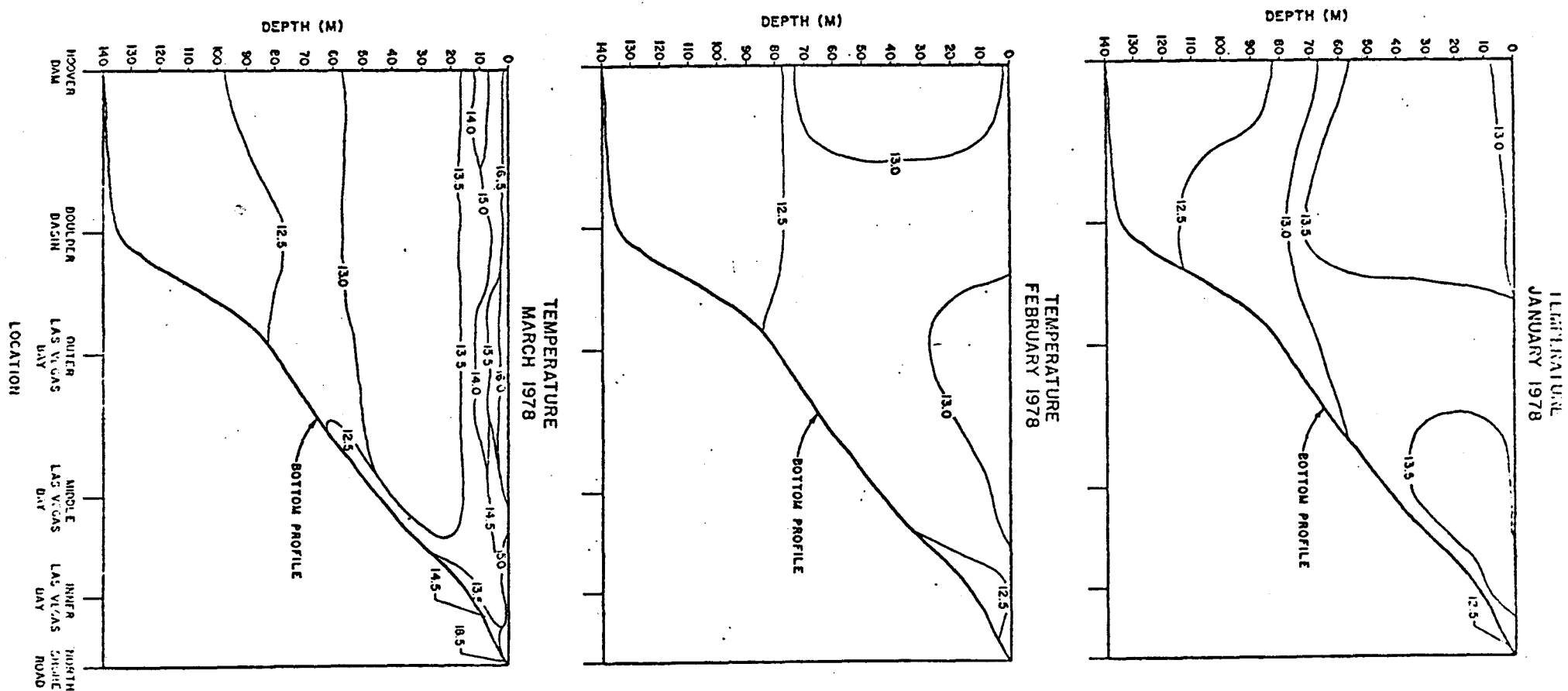
Figure 4.1.8   Temperature isotherms for Lower Basin stations,
Lake Mead in winter, 1978.
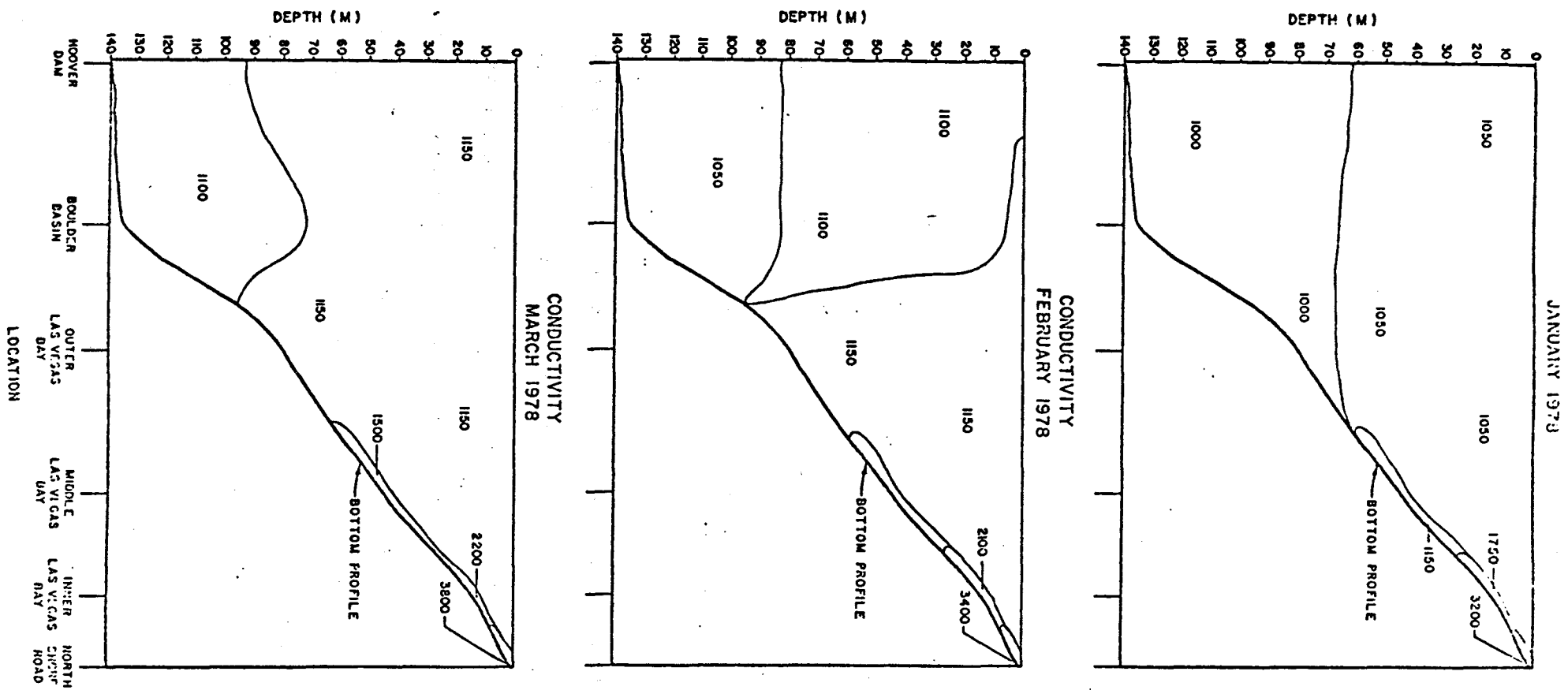
Figure 4.1.9 Conductivity isopleths for Lower Basin stations, Lake Mead in winter, 1978.

the inflow, and it appeared to move on to Boulder Canyon. The temperature
was slightly cooler above the thermocline, and slightly warmer below the
thermocline in Boulder Canyon and the upper end of Boulder Basin, reflecting
the inflow of river-water.

We observed a strong reverse current at the surface in Boulder Canyon
when we sampled in June. This was apparently caused by shear stress
generated along the thermocline as the inflow was forced into the narrow
canyon. The temperature profile at Echo Bay in June indicated that the
river-inflow also extended into the Overton Arm. The temperature at 5 m
and 10 m in Echo Bay was colder (22.5°C), and this isotherm was broader
than at the other stations (Fig. 4.1.11). Again, we noticed a fairly
substantial current moving along the surface towards Overton at Echo Bay
during the June sampling period. Thus, it appeared that part of the June
inflow was also diverted into the Overton Arm. The temperature at Overton
was considerably warmer than other stations, and there was no evidence
that the inflow extended much beyond Echo Bay.

The distribution of Colorado River inflow in June, 1978 was nearly
identical to that observed by Anderson and Pritchard (1951) for May, 1948.
However, we did not observe the turbidity plumes or detect the large
changes in salinity that they reported were associated with the spring
inflow. The formation of Glen Canyon Dam has decreased the silt load and
increased the TDS to the point where gradients in these parameters are
no longer created by the river-inflow.

The temperature structure in deep water (below 40 m) of the Lower and
Upper Basins had changed considerably by June. The isotherms below 35 m
were sloped down and toward the dam in the Boulder Basin (Fig. 4.1.10).
At Hoover Dam, the 12.5°C and 13.0°C dropped from 72 m and 42 m, respectively,

in May to 97 m and 62 m, respectively, in June. The lens of winter inflow (11.5°C) that had been located in Virgin Basin in May was split, and, in June, one cell was located below 115 m at Hoover Dam, a second cell was located at the bottom of Virgin Basin, and a third cell was located at the bottom of Temple Bar. Discharge from Hoover Dam was $9.3 \times 10^8 m^3$ in June. From the shape of the isotherms in Boulder Basin, and the location of the winter inflow, it appeared that discharge in June was replaced primarily from overlying water in Boulder Basin. This was reverse of the situation in May when replacement water originated primarily from the hypolimnion of the Upper Basin. However, formation of a circulation cell, and up-lake flow of hypolimnion water, in the Upper Arm in June may have created a reverse current sufficient to counteract the withdrawal current from Hoover Dam. Although fragments of the winter inflow were pulled up- and down-lake by these currents, the main cell remained intact in Virgin Basin. Apparently, neither current was sufficient to move this cell one way or the other and, therefore, replacement water for the June discharge had to be drawn down from overlying water in Boulder Basin.

The volume of Las Vegas Wash inflow was $5.2 \times 10^6 m^3$ in June. The temperature was 23.5°C which was slightly cooler than surface water in Las Vegas Bay (ca. 2.0°C) (Fig. 4.1.12). The conductivity of Las Vegas Wash was 3250 $\mu mhos \cdot cm^{-1}$, and this caused the Las Vegas Wash density current to flow along the bottom of the inner bay (Fig. 4.1.13). An interflow developed between the inner and middle bay where the density current flowed out along the thermocline (12 m). The density current then appeared to rise into the Outer Las Vegas Bay, as indicated by the upward slope of the isotherms from the middle to the outer bay and the slightly higher conductivity of surface waters at the outer bay (Fig. 4.1.13).

Summer Period

The volume of Colorado River inflow increased to $9.9 \times 10^8 m^3$ in July. The temperature of the inflow increased to between 19.1°C - 21.5°C (Fig. 4.1.14). The surface temperature of Lake Mead ranged from 26.7 - 28.2°C, and the thermocline was located at approximately 12 m. An underflow developed again at Iceberg Canyon because river-water was nearly 5°C colder than lake-water. This changed to a broad interflow at South Cove which moved down-lake below the thermocline and the 21.0°C isotherm. The thermocline was elevated at Iceberg Canyon and South Cove, but then receded at Temple Bar and remained unchanged across the reservoir to Hoover Dam. The surface temperature at Virgin Basin was slightly cooler than the Upper Arm or the Lower Basin. The temperature at Echo Bay was nearly equal to Virgin Basin but colder than Overton (Fig. 4.1.15), indicating that the inflow spread into the Overton Arm and Virgin Basin and was mixed to some degree with epilimnion water. The temperature differences in the epilimnion and metalimnion between the two basins were relatively small, and it could not be determined if the inflow passed through Boulder Canyon or reached Boulder Basin. However, the upward slope of the isotherm from Boulder Canyon to Boulder Basin (Fig. 4.1.14) does indicate a down-lake movement and influx of slightly cooler water into Boulder Basin in July.

There was no evidence to indicate that a deep circulation cell existed in the Upper Arm in July. The isotherms adjacent to, and below, the interflow were fairly uniform across Virgin Basin and the Upper Arm (Fig. 4.1.14). However, from June to July the 12.5°C isotherm dropped from 57 m to 75 m in Outer Las Vegas Bay (Fig. 4.1.16), from 58 m to 85 m in the Boulder Canyon and from 58 m to 72 m in Virgin Basin
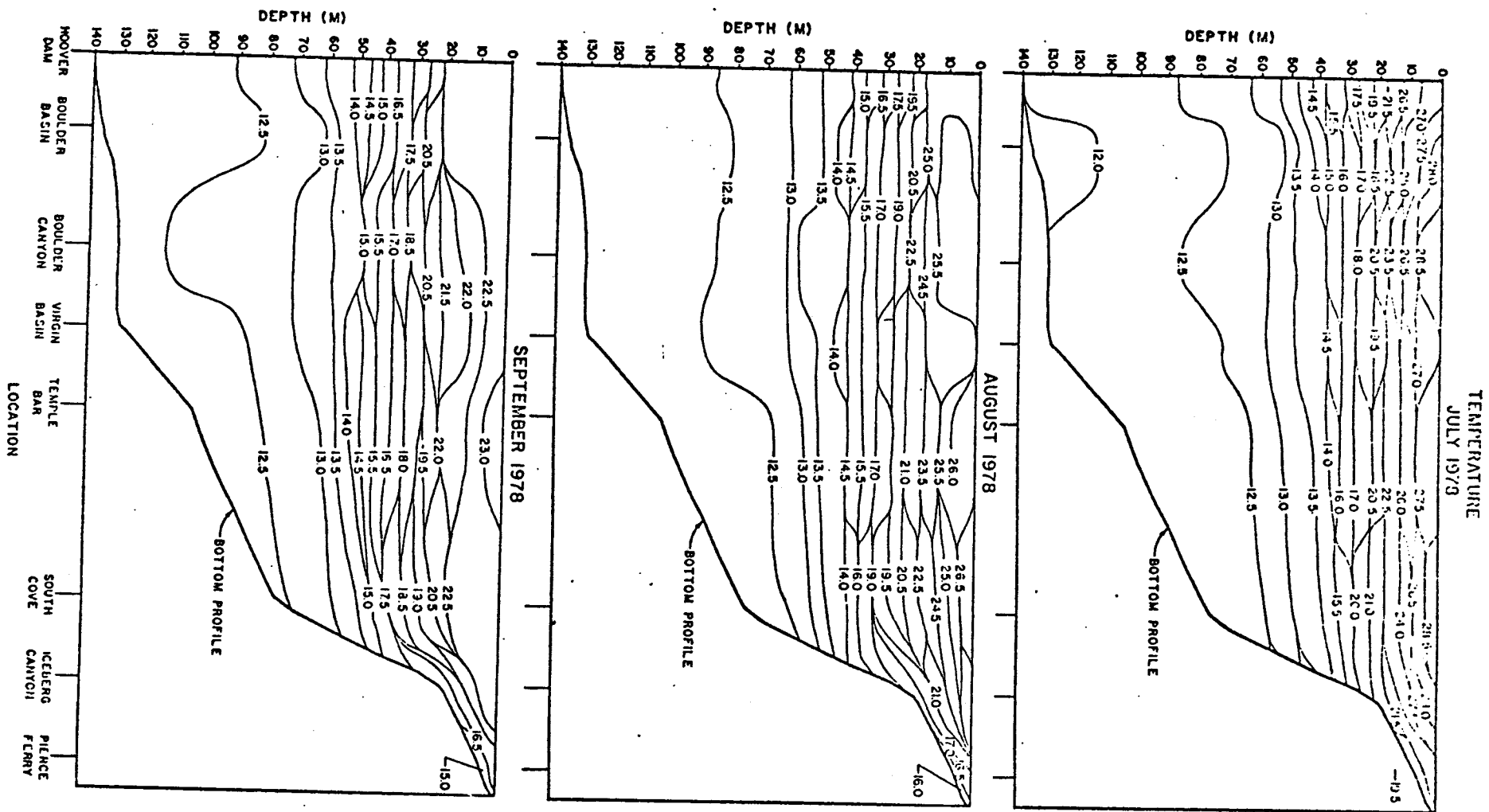
Figure 4.1.14 Temperature isotherms for Colorado River channel
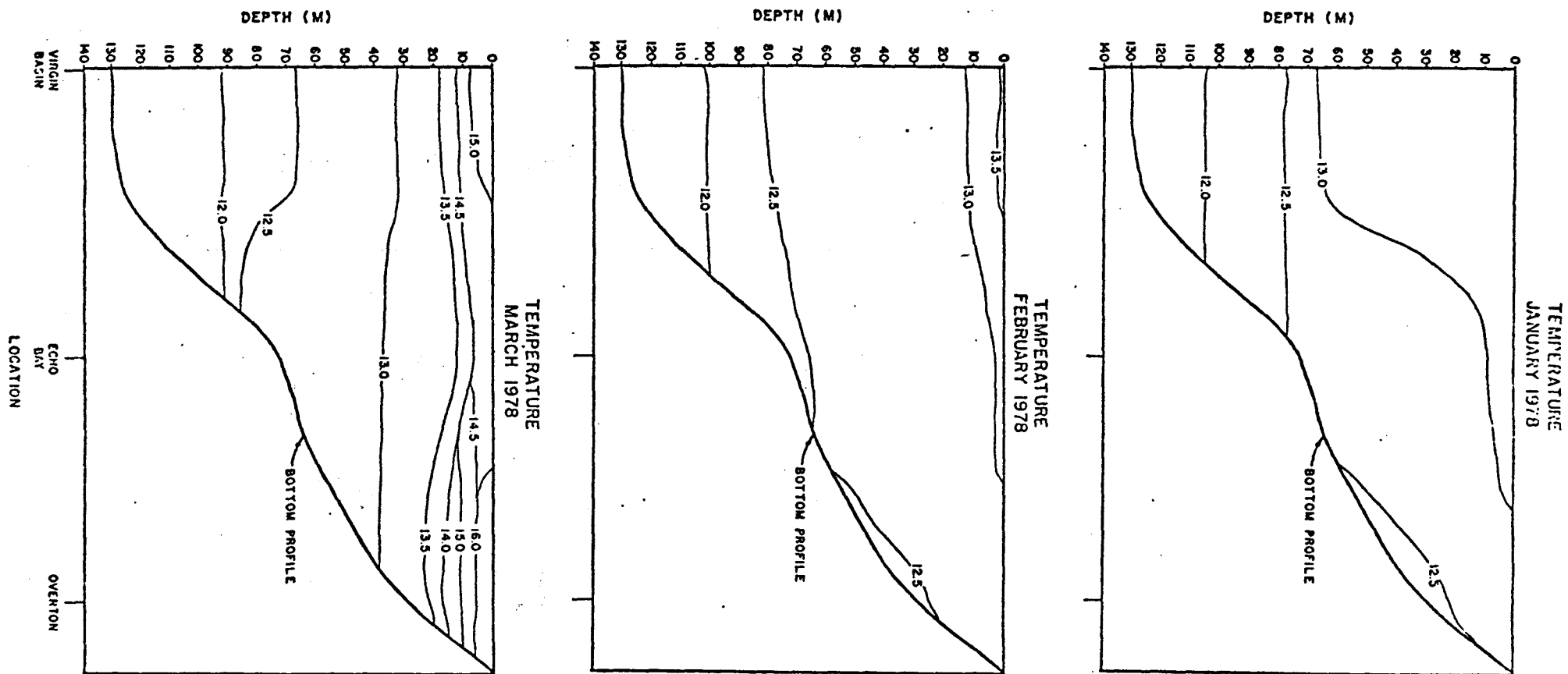stations, Lake Mead in summer, 1978.
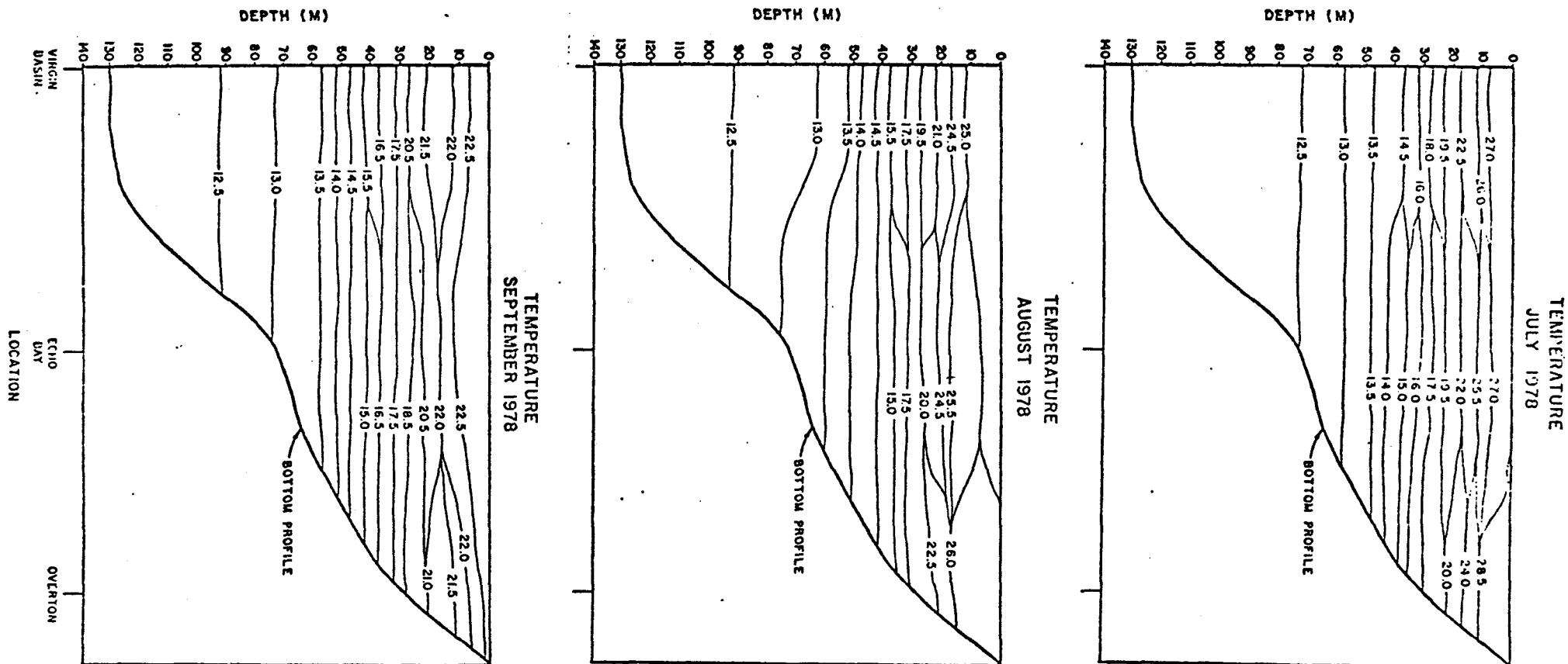
Figure 4.1.15 Temperature isotherms for Overton Arm stations,
Lake Mead in summer, 1978.

(Fig. 4.1.15). There was no appreciable change at Boulder Basin or Hoover Dam. However, the isotherms below 25 m were still sloped downward from Boulder Basin to Hoover Dam, as was also the case in June. A small cell of winter inflow (11.5°C) was located at the bottom of Boulder Basin, but none remained in the Upper Basin.

Discharge from Hoover Dam was $10.3 \times 10^8 m^3$ in July. It appeared that this was replaced by water drawn down-lake from Boulder Canyon and Virgin Basin, which, in turn, was replaced from overlying water (12.5°C and 13.0°C). The downward slope of the isotherms at Hoover Dam also indicated that some replacement water was drawn from warmer overlying water near the dam.

The Las Vegas Wash inflow volume was $5.0 \times 10^6 m^3$ in July. The temperature increased to 25.5°C (Fig. 4.1.16), and the conductivity was 3300 $\mu mhos \cdot cm^{-1}$ (Fig. 4.1.17). The density current still flowed primarily along the bottom of the inner bay, but formed an interflow along the thermocline between the Inner and Middle Las Vegas Bay. The main tongue of the density current was located at 12 m and extended to between the middle and outer bay where it was eventually dissipated by mixing.

The Colorado River inflow increased to $13.4 \times 10^8 m^3$ in August which was the maximum for the summer period. The temperature of the river decreased to between 15.7°C to 16.0°C, and the surface temperature in Lake Mead ranged from 24.5°C to 26.5°C (Fig. 4.1.14). The thermocline was located at approximately 17 m which was 5 m lower than in July. Again, an underflow developed in Iceberg Canyon but changed to an inter-flow at South Cove. The interflow was confined between the thermocline and the 14.0°C isotherm (12-32 m). The increased thickness of the interflow over that in previous months was caused by the higher discharge

TEMPERATURE
FEBRUARY 1978
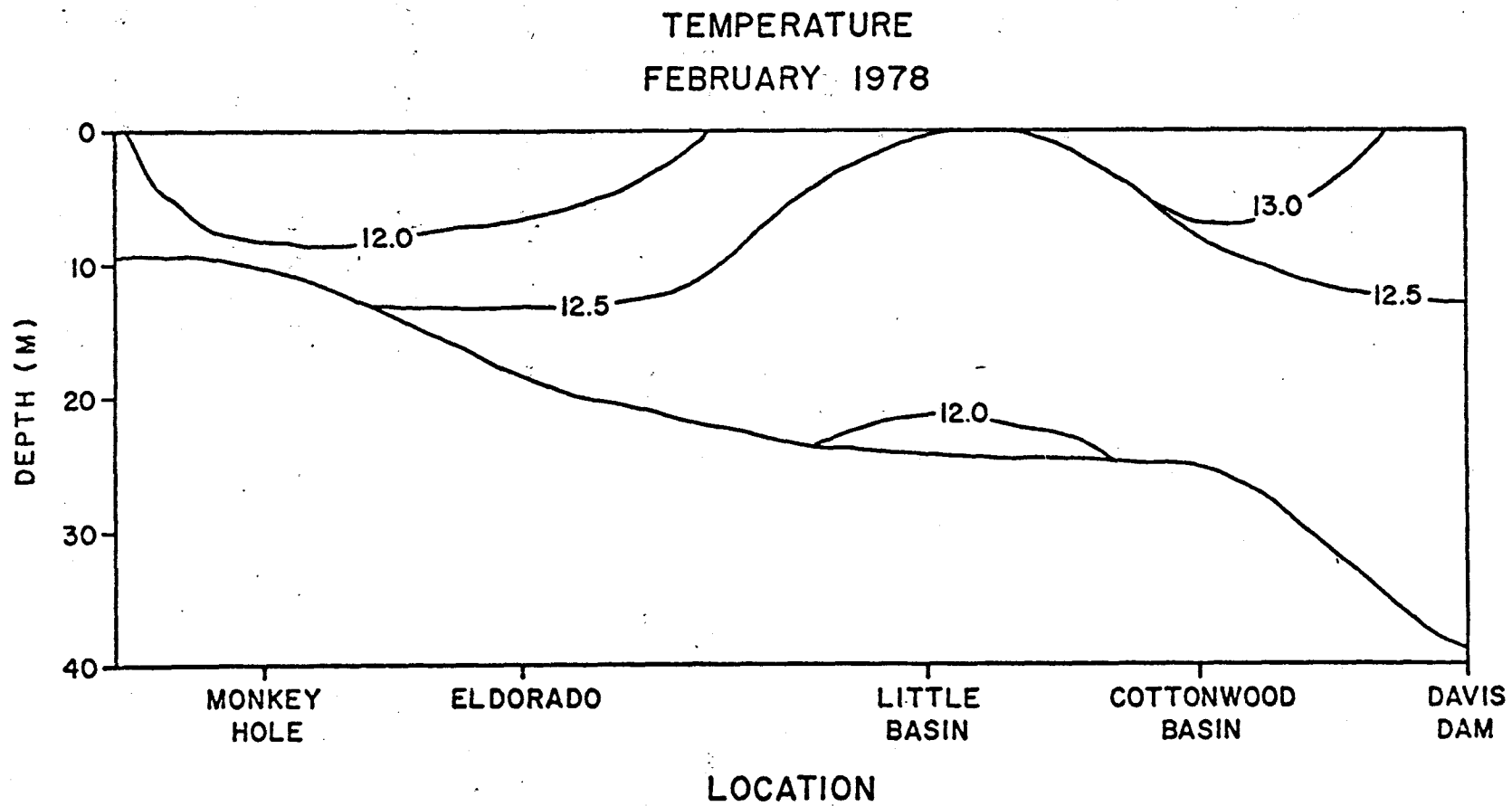
Figure 4.2.5 Temperature isotherms for Colorado river channel
stations, Lake Mohave in February, 1978.

TEMPERATURE
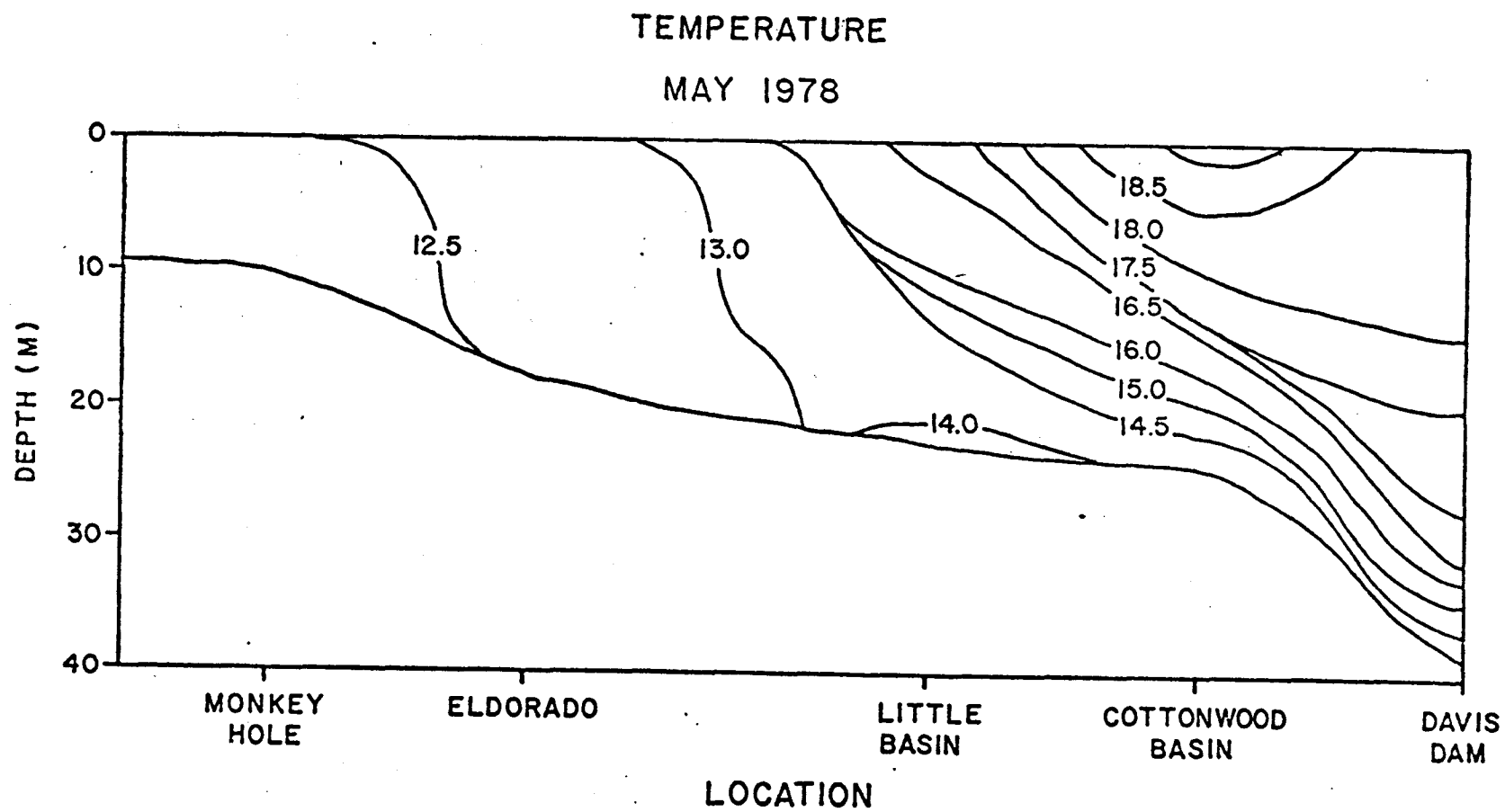
MAY 1978

Figure 4.2.6   Temperature Isotherms for Colorado River channel
stations, Lake Mohave in May, 1978.

relationship between inorganic phosphorus or ammonia concentration and the deep interflow, largely because the concentration of these nutrients was extremely low in the river, and nearly equal to the lake. Thus, inflow gradients did not develop for ammonia and phosphorus in the Upper Arm, regardless of the seasonal distribution of inflow. Ammonia concentrations were usually at, or below, detection throughout the Upper Basin during the study and, therefore, are not included in further discussions on nutrient distribution.

In late-November and early-December, underflow of the Colorado River increased nitrate concentration along the bottom of Iceberg Canyon and below 50 m at South Cove (Fig. 4.3.1). Nitrate profiles at Temple Bar, Virgin Basin and Boulder Canyon were uniform indicating that the inflow was fairly well mixed in up-lake areas during this period. High river-inflow in January increased mixing in up-lake areas, and the nitrate concentration increased accordingly at Iceberg Canyon. There was also a slight increase in phosphorus concentration during this period. Samples were not collected below 40 m in the winter, and the influence of the winter underflow on nutrient concentration down-lake could not be evaluated. However, since the lake was completely mixed, nitrate in deep water was probably uniform and equal in concentration to that in surface waters (ca. 300 $\mu g \cdot l^{-1}$). Phosphorus profiles were essentially uniform at 2.5 $\mu g \cdot l^{-1}$.

The concentration of nitrate in surface waters at Iceberg Canyon increased during the spring (April-May) when the river flowed into the epilimnion (Fig. 4.3.1). Temperature isotherms for this period indicated that the inflow extended down-lake to Temple Bar. This was not associated with any appreciable increase in nitrate because first, the concentration in the lake (ca. 300 $\mu g \cdot l^{-1}$) was nearly equal to the river (ca. 325 $\mu g \cdot l^{-1}$)

LAKE MEAD NUTRIENT PROFILES

μG·L⁻¹
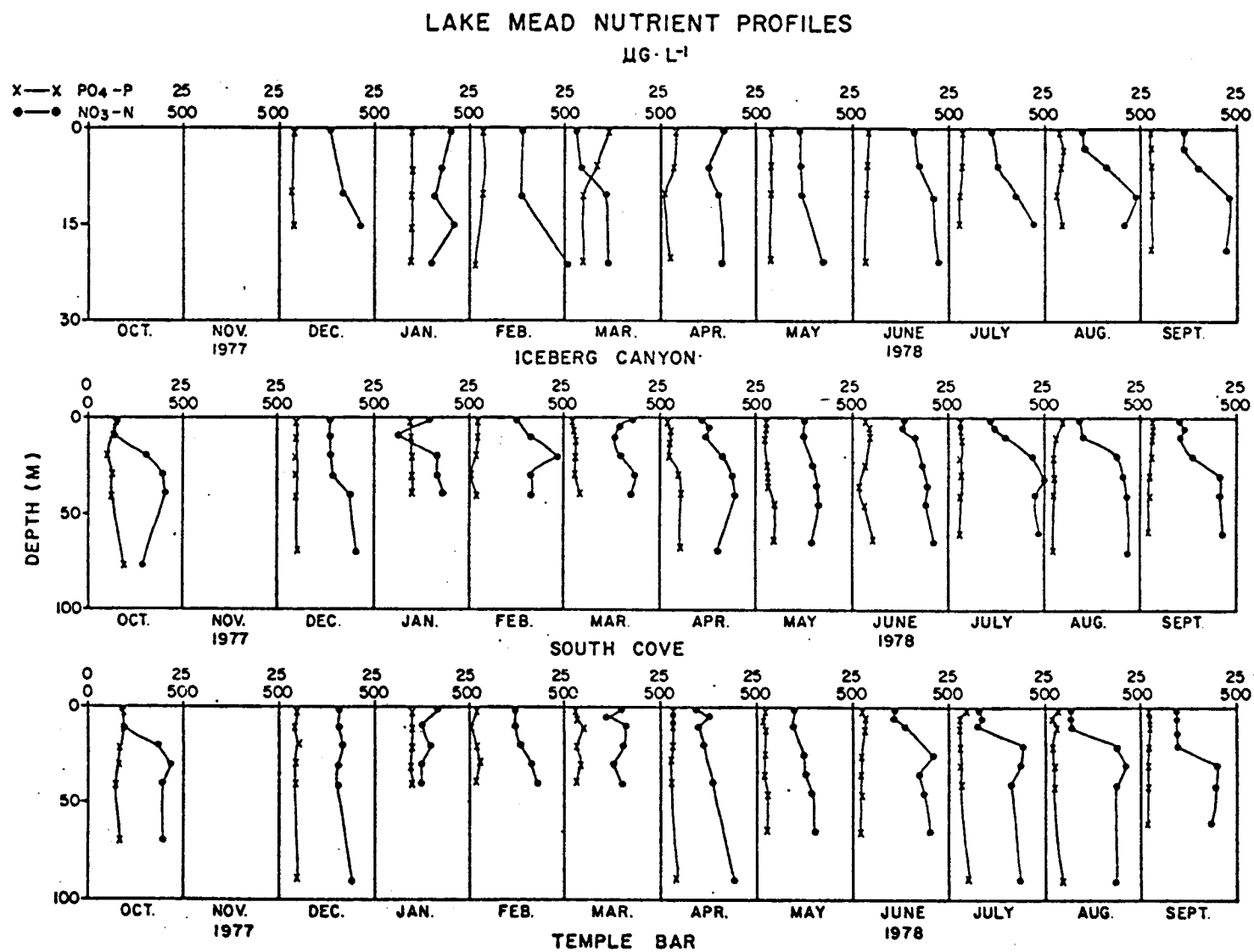
Figure 4.3.1 Nutrient profiles in the Upper Arm,
Lake Mead.

59

and, second, phytoplankton productivity had increased and this tended to reduce nitrate in the surface waters.

Nitrate concentration increased in bottom waters of Iceberg Canyon in June, and, from July to September, a sharp gradient existed between lake-water (200 $\mu g \cdot l^{-1}$) and river-water (400-500 $\mu g \cdot l^{-1}$) (Fig. 4.3.1). This gradient was maintained by high discharge and prolonged underflow of Colorado River water at Iceberg Canyon during the summer. Vertical nitrate gradients developed throughout the lake in the summer as a result of nitrate uptake by phytoplankton. This gradient was further increased in the Upper Arm by continual inflow of nitrate below the euphotic zone from the Colorado River inflow. This was especially evident at South Cove and Temple Bar where nitrate concentration increased to 400-425 $\mu g \cdot l^{-1}$ in the metalimnion and upper hypolimnion during the summer. A nitrate gradient also existed at Virgin Basin and Boulder Canyon during late summer, and there was a slight increase in nitrate concentration in the metalimnion over that in early summer (Fig. 4.3.1). This, however, may also have been caused by remineralization of nitrogen bound in algae and seston sedimenting from surface layers.

4.3.2 Overton Arm

The vertical and seasonal variation of nutrient concentration in the Overton Arm was similar to that in Virgin Basin. Inorganic phosphorus concentrations were essentially uniform at 2.5 $\mu g \cdot l^{-1}$ throughout the year (Fig. 4.3.2). In the winter, nitrate was approximately 300 $\mu g \cdot l^{-1}$ in surface waters (Fig. 4.3.2), and a vertical nitrate gradient developed in the summer as phytoplankton reduced nitrate to 100 $\mu g \cdot l^{-1}$ in the euphotic zone. However, in the hypolimnion the nitrate concentration remained near 300 $\mu g \cdot l^{-1}$ throughout the year. The slight increase of nitrate in bottom
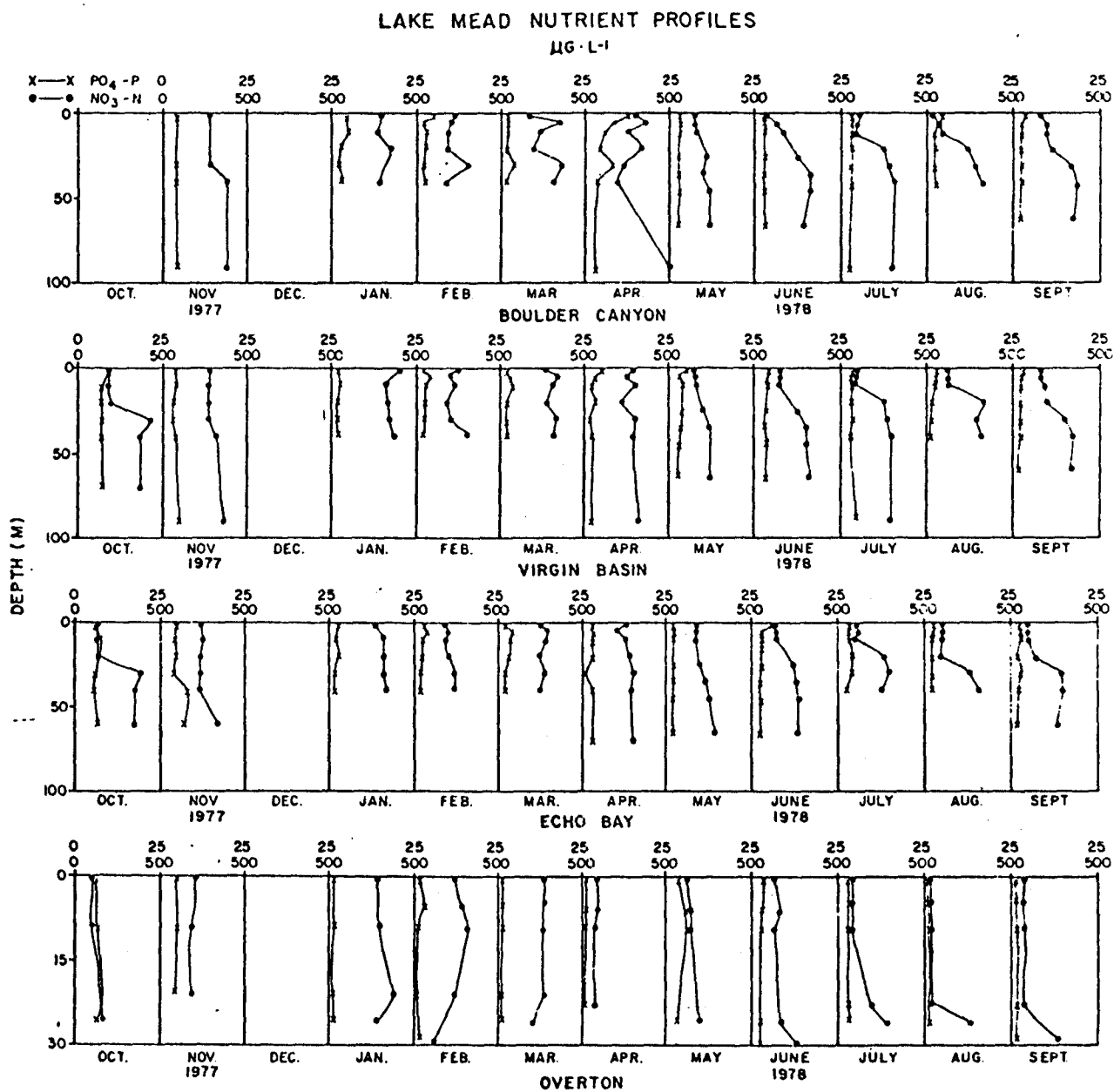
Figure 4.3.2 Nutrient profiles in the Overton Arm, Lake Mead and Virgin Basin.

waters at Overton in late summer may have been caused by inflow from the Virgin and Muddy Rivers. Beyond that, these inflows did not appear to have any appreciable influence on nutrient concentration in the Overton Arm.

4.3.3 Las Vegas Wash

The wastewater from Las Vegas Wash was high in inorganic nitrogen and phosphorus, and seasonal changes in the distribution of the Las Vegas Wash density current had a direct influence on nutrient concentration in Las Vegas Bay and Boulder Basin.

In the fall, the concentration of phosphorus in the epilimnion was high at the inner bay but decreased considerably at middle bay. It then remained similar throughout the outer bay and Boulder Basin. Nitrate concentration in the epilimnion remained low throughout Las Vegas Bay and Boulder Basin in the fall (Fig. 4.3.3). However, there was a definite increase in the phosphorus and nitrate concentration in the metalimnion of the middle bay in October and November when the density current flowed along the thermocline (Fig. 4.3.3). There was also a slight increase in phosphorus concentration of the hypolimnion in Boulder Basin and Hoover Dam (Fig. 4.3.3). The influence of Las Vegas Wash inflow on nitrate concentration was limited primarily to the inner and middle bay because of rapid uptake by phytoplankton.

In the winter (January-February), nitrate and phosphorus concentrations increased sharply in the density current near the bottom of the inner bay. In the middle and outer bay, and Boulder Basin, nitrate and phosphate concentrations were nearly uniform throughout the water column due to vertical mixing. The concentration of nitrate in Las Vegas Bay and Boulder Basin was similar to that of the Upper Basin (ca. 300 $\mu g \cdot l^{-1}$), but there

LAKE MEAD NUTRIENT PROFILES

μG·L⁻¹

Figure 4.3.3   Nutrient profiles in the Lower Basin,
Lake Mead.

was a considerable difference in phosphate concentration. Phosphate ranged

from 25-30 $\mu g \cdot l^{-1}$ in the surface water of the inner bay to about 15 $\mu g \cdot l^{-1}$

in the rest of Boulder Basin (Fig. 4.3.3). In the Upper Basin, phosphate

concentration rarely exceeded 5 $\mu g \cdot l^{-1}$ during the winter (Fig. 4.3.3).

This difference was caused by the high phosphorus loading of Las Vegas

Bay and Boulder Basin from Las Vegas Wash.

The density current flowed along the bottom of the inner bay, and the

concentration of inorganic nutrients remained high during the spring

(March-May) (Fig. 4.3.3). There was a near linear increase in the

concentration of nitrate and phosphorus at the middle bay as the density

current progressively ascended from the bottom. In April and May, this

increased the phosphorus concentration of the hypolimnion throughout Las

Vegas Bay and Boulder Basin but had no appreciable influence on nitrate

concentration in the hypolimnion beyond the middle bay.

The density current still flowed primarily along the bottom of the

inner bay during the summer (June-September), and the concentration of

nutrients increased accordingly. However, mixing increased during this

period and phosphorus concentration increased accordingly in the surface

waters of the inner bay. Nitrate and ammonia, however, remained low in

the inner bay and the rest of the Lower Basin, due to uptake by phyto-

plankton. The formation of a shallow interflow, in the middle bay during

the summer increased the phosphorus concentration in the metalimnion and

hypolimnion during June and July. In August and September, the concentration

of phosphorus increased to approximately 20 $\mu g \cdot l^{-1}$ in the epilimnion of the

middle bay and 5-10 $\mu g \cdot l^{-1}$ (Fig. 4.3.3) at the outer bay and Boulder Basin.

This occurred despite high phytoplankton productivity, indicating that the

density current provided a substantial phosphorus input to the outer Las

Vegas Bay and Boulder Basin in late summer.

4.4 Influence of Currents on Nutrient Distribution in Lake Mohave

Essentially all of the nutrient input to Lake Mohave was derived from discharge at Hoover Dam. Nutrient concentrations below Hoover Dam were relatively constant throughout the year. Nitrate and dissolved phosphorus concentration averaged about 400 $\mu g \cdot l^{-1}$ and 15 $\mu g \cdot l^{-1}$, respectively (Fig. 4.4.1). Ammonia concentration was usually less than 20 $\mu g \cdot l^{-1}$ both in the river and in the lake but occasionally ranged as high as 200 $\mu g \cdot l^{-1}$ (Fig. 4.4.1). The high ammonia concentration was most likely derived from the ammonification of organic nitrogen. The only other potential source of ammonia was from the Willow Beach Trout Hatchery, but discharge from the hatchery represented less than 1% of the flow in the river and, therefore, probably had very little influence on ammonia concentration in the lake.

The concentration of nitrate varied seasonally in relation to thermal stratification. In the winter, nitrate was relatively uniform due to mixing of river- and lake-water. A horizontal nitrate gradient developed at down-lake stations in the spring. This ranged from 300-400 $\mu g \cdot l^{-1}$ at Monkey Hole to less than 200 $\mu g \cdot l^{-1}$ at Davis Dam (Fig. 4.4.1), largely because of nitrate uptake by phytoplankton. Higher nitrate concentration also occurred at the up-lake stations, Little Basin and Eldorado Canyon, because of partial mixing of river-water. Nitrate concentration in the epilimnion was reduced to below 20 $\mu g \cdot l^{-1}$ at the surface in the summer because of uptake by phytoplankton. Nitrate concentration increased at Davis Dam in late summer because of the upwelling of hypolimnion water that was high in nitrate (ca. 200-300 $\mu g \cdot l^{-1}$).

There was no seasonal change in dissolved phosphorus, as there was for nitrate. Dissolved phosphorus was fairly uniform vertically, except

LAKE MOHAVE NUTRIENT CONCENTRATIONS

μG·L⁻¹

Figure 4.4.1 Nutrient profiles in Lake Mohave.
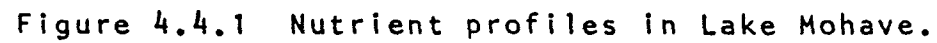
for periodic increases in the hypolimnion. This could have been caused by release of phosphorus from decomposing algae settling to the bottom. Stripping of dissolved phosphorus by phytoplankton in the epilimnion did not occur, apparently because of the lower requirement and faster turnover rate of phosphorus in comparison with nitrogen.

4.5 Inorganic Nutrient Budgets

4.5.1 Lake Mead

Nutrient budgets have long been used as a means of assessing the nutrient status of lakes and reservoirs (Wetzel 1975). The basic approach of constructing a nutrient budget is to measure the flow rate and nutrient concentration of the inputs and outputs. A budget can then be computed by the following simple equation:

$$B = (C_i \times V_i) - (C_0 \times V_0) \, k_i ---k_n \qquad (1)$$

Where B = nutrient balance ($kg \cdot day^{-1}$, or $kg \cdot month^{-1}$, or $kg \cdot year^{-1}$)

C_i = nutrient concentration of input ($mg \cdot m^{-3}$)

V_i = flow rate of input ($m^3 \cdot sec.^{-1}$)

C_0 = nutrient concentration of output ($mg \cdot m^{-3}$)

V_0 = flow rate of output ($m^3 \cdot sec.^{-1}$)

$k_i ---k_n$ = unit conversion factors

If $B > 0$, the reservoir is accumulating nutrients. If $B < 0$, the reservoir is losing nutrients. Finally, if $B = 0$, the reservoir is at nutrient equilibrium.

We used this approach to construct inorganic nitrogen (ammonia and nitrate) and phosphorus (phosphate) budgets for Lake Mead using input from the Colorado River and Las Vegas Wash and output below Hoover Dam (Table 4.5.1). The Muddy River and Virgin River provide a small nutrient input relative to these inputs (EPA 1978a) and, therefore, were not included

Table 4.5.1   Inorganic nitrogen and phosphorus loading and discharge for Lake Mead.

$(1977-1978)$ $(kg \cdot yr^{-1})$

Nutrient	Input			Output
	Colorado River	Boulder Canyon	Las Vegas Wash	Hoover Dam
Nitrate (N)	45.63×10^5	25.6×10^5	3.49×10^5	29.8×10^5
Ammonia (N)	1.42×10^5	1.21×10^5	3.24×10^5	1.25×10^5
Total Inorganic Nitrogen (N)	47.05×10^5	26.8×10^5	6.73×10^5	31.05×10^5
Phosphate (P)	56.8×10^3	29.8×10^3	136.6×10^3	110.6×10^3
Total Phosphorus (P)	198.7×10^3	--	263.1×10^3	--
Inorganic Nitrogen: Inorganic Phosphorus Ratio	$\dfrac{82.8}{1}$	$\dfrac{89.9}{1}$	$\dfrac{4.9}{1}$	$\dfrac{28.1}{1}$

in the budgets.

A rather unique situation existed in Lake Mead where the Colorado River provided most of the inorganic nitrogen input (87.5%), but Las Vegas Wash contributed most of the inorganic phosphorus input (70.6%) (Paulson and Baker 1979a) (Table 4.5.1). Input from the Colorado River was severely phosphorus deficient at an N:P of 83, and Las Vegas Wash was nitrogen deficient at an N:P of 5. The combined input of both sources yielded an N:P of 28. Lake Mead retained 42.3% of the inorganic nitrogen input and 42.8% of the inorganic phosphorus input (Table 4.5.2). The N:P of the discharge at Hoover Dam was 28 which was identical to the inputs (Table 4.5.1). Thus, on the whole, processes operating in the reservoir retained an equal proportion of inorganic nitrogen and phosphorus. However, this changed considerably when separate budgets were estimated for the Lower and Upper Basin.

Nutrient concentrations were measured, monthly, at several depths in Boulder Canyon in an effort to better estimate true nutrient loading of the Lower Basin from the Colorado River. Nutrient budgets were estimated for Virgin Basin using input from the Colorado River and output at Boulder Canyon. These were calculated on the basis of depth, integrated average nutrient concentrations at Boulder Canyon multiplied by monthly discharge from Hoover Dam. The budget for the Lower Basin was estimated using input from Boulder Canyon and Las Vegas Wash and output below Hoover Dam (Table 4.5.1).

The N:P of the input and output for the Upper Basin averaged 83 and 90, respectively, compared to 20 and 28, respectively, for the Lower Basin. Nitrogen and phosphorus retention averaged 43 and 48%, respectively, for the Upper Basin but decreased to 7.4% for nitrogen and 33.5% for phosphorus

Table 4.5.2   Inorganic nitrogen and phosphorus retention for each basin and all of
                Lake Mead.

	Lower Basin[1]	Upper Basin[2]	Whole Lake[3]
Nitrogen (nitrate + ammonia) retention	7.39%	43.0%	42.2%
Phosphorus (phosphate) retention	33.5%	47.5%	42.8%

1   Input at Boulder Canyon and Las Vegas Wash, output at Hoover Dam

2   Input at Colorado River (Pierce Ferry), output at Boulder Canyon

3   Input at Colorado River (Pierce Ferry) and Las Vegas Wash, output at Hoover Dam

in the Lower Basin (Table 4.5.2). Thus, in the Upper Basin, equal proportions of nitrogen and phosphorus were retained, and these values were similar to that estimated for the whole reservoir. However, nitrogen, and to a lesser degree phosphorus, retention decreased considerably in the Lower Basin.

4.5.2 Lake Mohave

Nutrient input to Lake Mohave was determined by multiplying the monthly discharge by the nutrient concentration in samples collected below the dam. Output was determined from the nutrient concentration in the hypolimnion (20 m) and monthly discharge at Davis Dam. Nutrient concentrations at 20 m appeared to best represent the withdrawal zone of the Davis Dam discharge and were used in estimating the budget because samples were not routinely collected below Davis Dam.

Lake Mohave retained 36.6% of the dissolved phosphorus and 30.5% of the inorganic nitrogen input from Hoover Dam (Table 4.5.3). This represents nearly proportional retention of phosphorus and nitrogen and, as in Lake Mead, indicates that these nutrients were being retained in a common pool. This was probably due to the assimilation of these nutrients by phytoplankton. However, the amount of phosphorus and nitrogen retention was greater in Lake Mohave than what was expected because of the short hydraulic retention time (ca. 80 days). The relatively high nutrient retention rate appears to be due to greater availability of the nutrient load in Lake Mohave. The surface to volume ratio in Lake Mohave (50:1) is much greater than Lake Mead (18:1) which permits greater mixing of the river inflow. Therefore, a greater percentage of the inorganic nutrient input to Lake Mohave was made available to and assimilated by the phytoplankton. However, because of the shallow depth of Lake Mohave, and

Table 4.5.3   Inorganic nitrogen and dissolved phosphorus

budget for Lake Mohave (1977) kg·yr.$^{-1}$.

Nutrient	Input Hoover Dam	Output Davis Dam
Inorganic nitrogen	3.40×10^6	2.36×10^6
Dissolved phosphorus	1.37×10^5	8.68×10^4
Inorganic nitrogen: dissolved phosphorus ratio	24.8	27.2

faster flushing rate, a greater percentage of these nutrients were also

discharged in organic form at Davis Dam (Priscu 1978). This accounts for

the relatively high retention of inorganic nutrients. However, because

nutrients were tied up in the organic form, total nutrient retention in

the reservoir was very low. Priscu (1978) estimated that only 2.8% of the

total phosphorus and 3.9% of the total nitrogen loads were retained due

to the high flushing of organic nutrients from Davis Dam.

4.6 Vertical Distribution of Phytoplankton Productivity

4.6.1 Lake Mead

The vertical distribution of phytoplankton productivity

in Lake Mead varied considerably, depending on the season and location

in the reservoir. There was considerable seasonal variation in the

productivity curves at Iceberg Canyon that was related to the distribution

of nutrients and silt from the Colorado River inflow. The productivity

in the upper 5 m was usually higher at Iceberg Canyon (ca. 10 mg $C \cdot m^{-3} \cdot hr^{-1}$)

(Fig. 4.6.1) than the rest of the Upper Basin (ca. 5 mg $C \cdot m^{-3} \cdot hr^{-1}$)

(Fig. 4.6.2). Except for April, this was not as great as would

be expected near a major inflow. However, for most of the year, the

Colorado River formed an underflow in Iceberg Canyon and, therefore,

nutrient inflow occurred primarily below the euphotic zone. Moreover,

the continuous inflow of silt reduced light penetration to the point where

productivity was usually reduced at, and below 10 m (Table 4.6.1). Light

extinction coefficients were high and ranged from .430 to .632$\cdot m^{-1}$ for

the period when we made routine measurements (April-Sept. 1978)(Table 4.6.1).

The maximum productivity (80 mg $C \cdot m^{-3} \cdot hr^{-1}$) that was measured in the Upper

Basin occurred at 1 m in April when the Colorado River formed an overflow

in Iceberg Canyon. The overflow was accompanied by an increase in

LAKE MEAD

PHYTOPLANKTON PRODUCTIVITY

MG C·M⁻³·HR.⁻¹
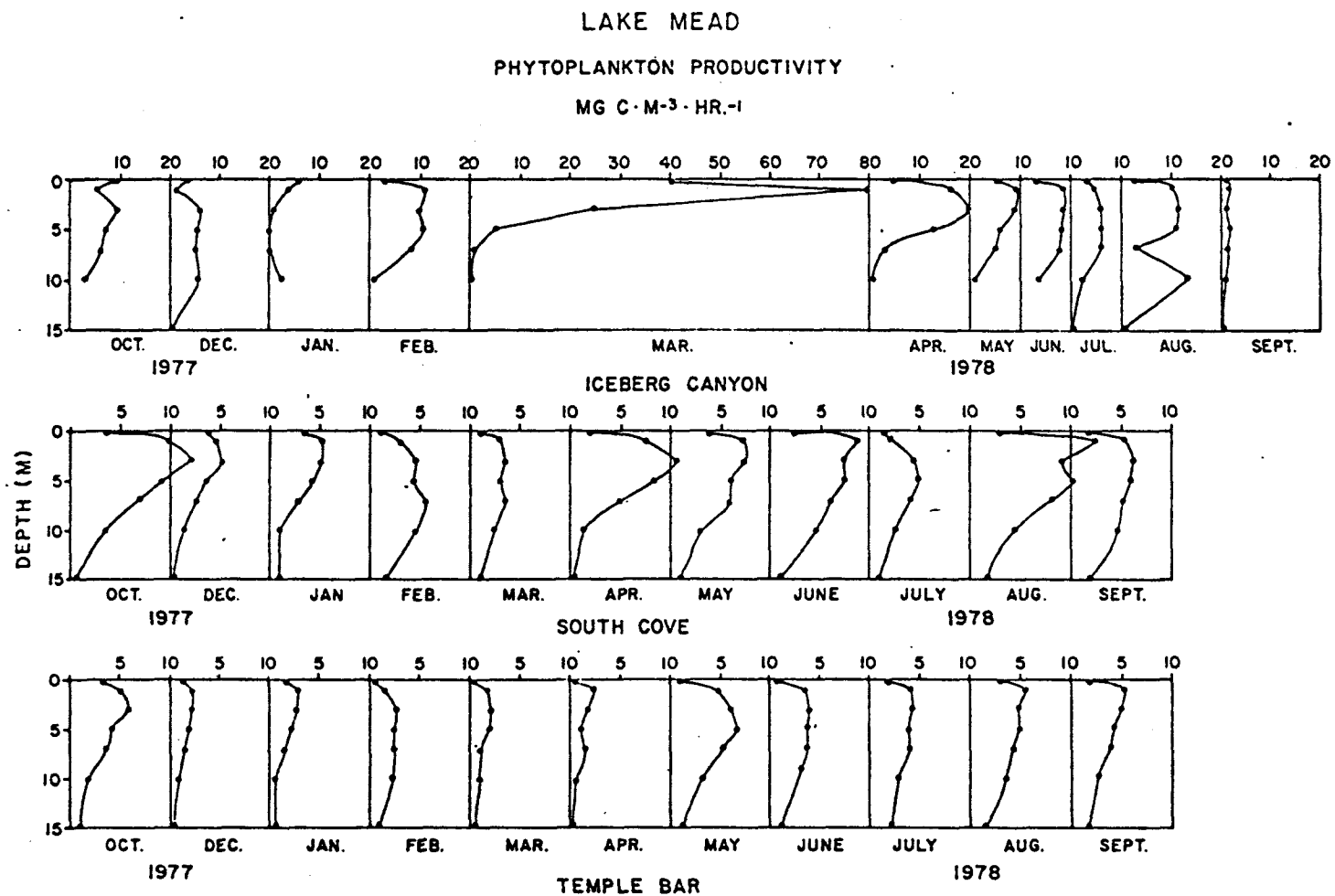
Figure 4.6.1   Phytoplankton productivity profiles in the
Upper Arm, Lake Mead.

LAKE MEAD

PHYTOPLANKTON PRODUCTIVITY

MG C · M⁻³ · HR.⁻¹
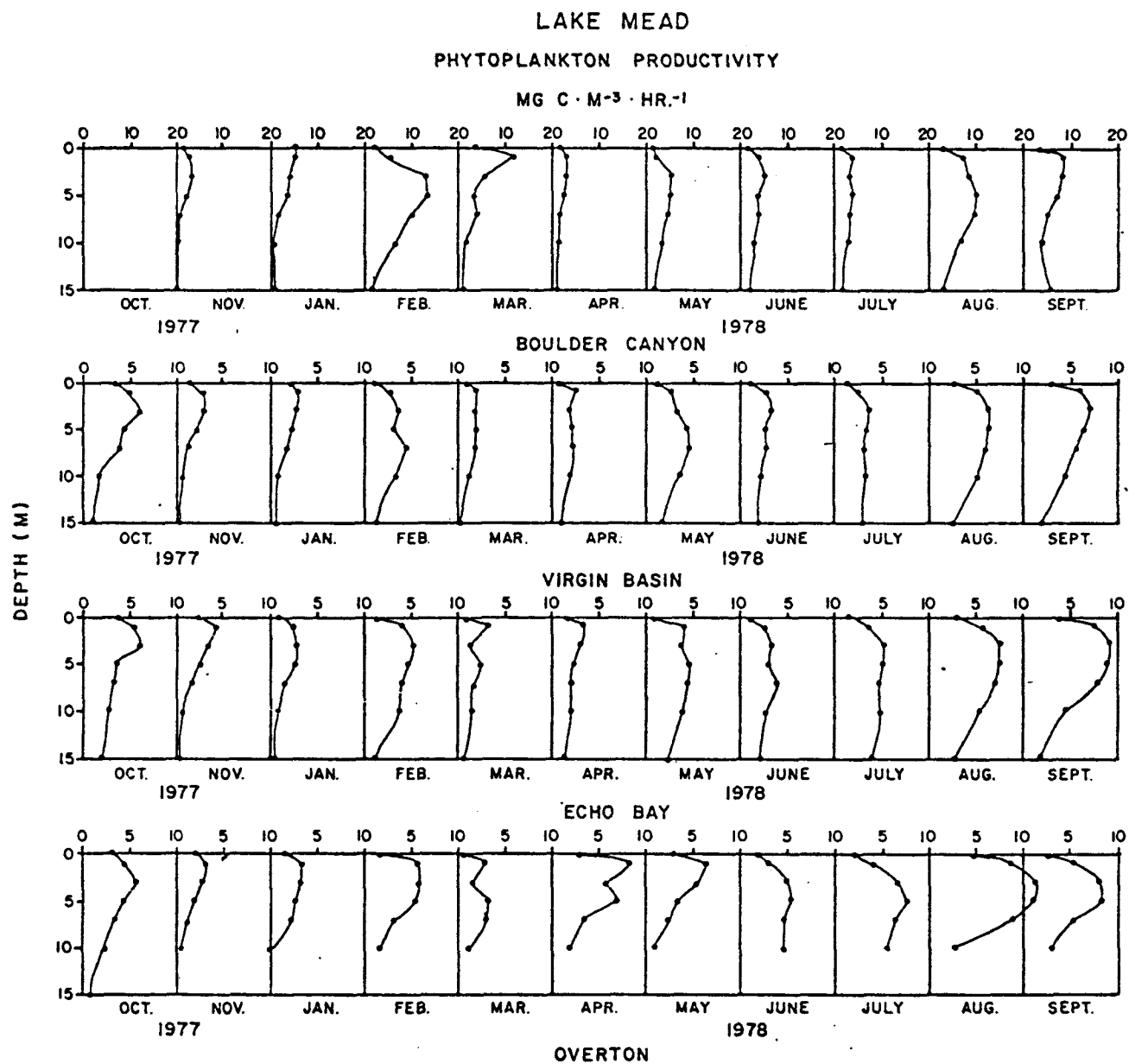
Figure 4.6.2   Phytoplankton productivity profiles in the
Overton Arm and Virgin Basin, Lake Mead.

Table 4.6.1   Light extinction coefficients for Lake Mead (April 1978 -
                September 1978) computed from linear regression of the
                log of light transmittance versus depth.

Station	Light Extinction Coefficients per m					
	April	May	June	July	August	September
Inner Las Vegas Bay	.359	.536	.480	.676	.907	.879
Middle Las Vegas Bay	.243	-	.337	.444	.694	.681
Outer Las Vegas Bay	.236	.310	.255	.265	.526	.584
Boulder Basin	.201	.298	.239	.275	.563	.416
Hoover Dam	.230	.303	.254	.248	-	-
Boulder Canyon	.164	.217	.219	.212	.245	.224
Virgin Basin	.162	.195	.195	.223	-	-
Echo Bay	.191	.207	.196	.232	.227	.246
Overton	.470	.479	.293	.364	.276	.337
Temple Bar	.193	.280	.286	.250	.242	.213
South Cove	.343	.330	.313	.282	.273	.235
Iceberg Canyon	.632	.542	.482	.507	.462	.430

phosphorus concentration that was probably sufficient to trigger the higher productivity. However, the productivity decreased rapidly with depth due to high light extinction from shading by phytoplankton cells and silt.

The influence of silt from the Colorado River inflow was greatly reduced in down-lake areas. The extinction coefficients measured at South Cove were slightly higher than the main-reservoir stations in the Upper Basin (Temple Bar, Virgin Basin, Boulder Canyon and Echo Bay) during the spring (Table 4.6.1). This indicated that some silt was transported down-lake by the spring overflow. However, for the rest of the year, the extinction coefficients at South Cove were similar to the other stations in the Upper Basin for a particular sampling period. The productivity curves were also similar and characteristic of oligotrophic-mesotrophic conditions.

The productivity near the surface was usually less than 1 mg $C \cdot m^{-3} \cdot hr^{-1}$, regardless of the season or location in the Upper Basin (Figs. 4.6.1, 4.6.2). The maximum productivity usually occurred near 5 m, and this ranged from 2-5 mg $C \cdot m^{-3} \cdot hr^{-1}$ for most of the year. However, in August and September, the maximum productivity increased to between 7 and 10 mg $C \cdot m^{-3} \cdot hr^{-1}$. The productivity decreased to less than 1 mg $C \cdot m^{-3} \cdot hr^{-1}$ at 15 m during the fall and winter, but, from April to September, this ranged from 2-4 mg $C \cdot m^{-3} \cdot hr^{-1}$ and was often equal to the maximum productivity (Figs. 4.6.1, 4.6.2). There was a direct relationship between light extinction and productivity at the main reservoir stations in the ꞉er Basin. For the period of measurement (April - September), light extinction was lowest in the spring, but then increased proportionally to productivity in the late summer (Table 4.6.1), reflecting self-shading caused by the growth of

phytoplankton.

The productivity curves at Overton were similar to the other stations in the Upper Basin during the fall and winter (Fig. 4.6.2). However, from April to September, the productivity at Overton was slightly higher than the rest of the Upper Basin (Fig. 4.6.1) due to some nutrient inflow from the Virgin and Muddy Rivers. The extinction coefficients were also higher, but this was not due entirely to phytoplankton biomass. The high light extinction in April and May was, in part, caused by mixing of silt-ladened inflow from the Virgin and Muddy Rivers.

The seasonal trends in the productivity curves in the Lower Basin were similar to those in the Upper Basin. However, the productivity was higher in the Lower Basin, and there was considerably more spatial and vertical variation than in the Upper Basin. The productivity in the Inner Las Vegas Bay was consistently higher than the rest of Lake Mead (Fig. 4.6.3). The maximum productivity usually occurred at 1 m and ranged from 2 mg $C \cdot m^{-3} \cdot hr^{-1}$ in February to 330 mg $C \cdot m^{-3} \cdot hr^{-1}$ in August. The productivity decreased rapidly with depth and, only in May and June, did any appreciable productivity occur at, or below, 7 m. Light extinction varied in direct relation to the productivity (.359 in April to $.907 \cdot m^{-1}$ in August) (Table 4.6.1). The depth of the euphotic zone in the inner bay appeared to be limited primarily by phytoplankton biomass rather than silt or other substances from Las Vegas Wash.

The productivity at the Middle Las Vegas Bay was approximately half as high as the inner bay. The maximum productivity usually occurred at 1-3 m and ranged from 10 mg $C \cdot m^{-3} \cdot hr^{-1}$ in April to 140 mg $C \cdot m^{-3} \cdot hr^{-1}$ in August (Fig. 4.6.3). The euphotic zone was slightly greater at the middle bay but, only from May - July, did any significant productivity occur at,

LAKE MEAD

PHYTOPLANKTON PRODUCTIVITY

MG C·M⁻³·HR⁻¹
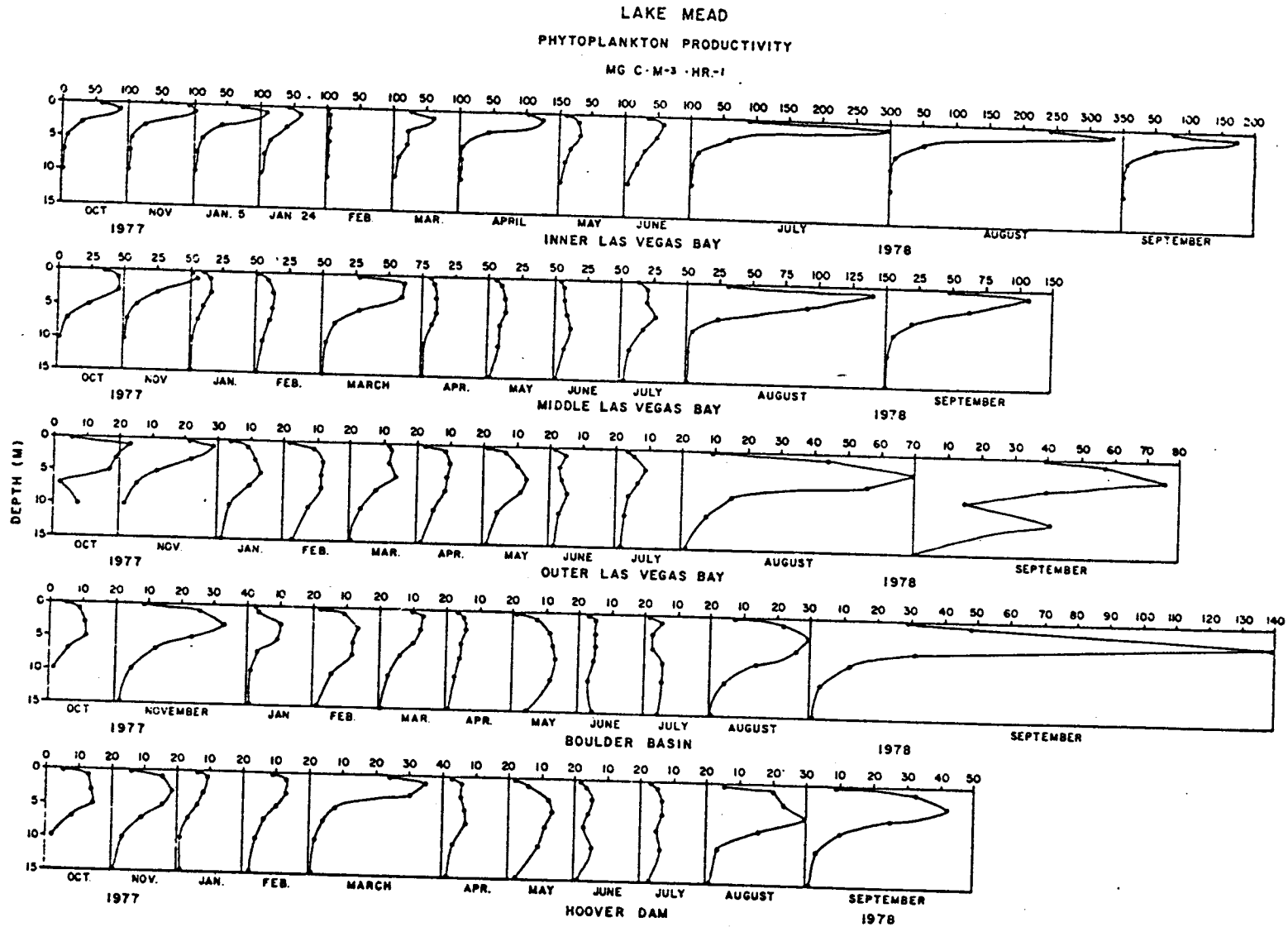
Figure 4.6.3   Phytoplankton productivity profiles in the
Lower Basin, Lake Mead.

or below, 10 m. Light extinction was also lower than at the inner bay but still increased proportionally to productivity in late summer.

The productivity curves at the Outer Las Vegas Bay, Boulder Basin and Hoover Dam were similar for a particular sampling period. Maximum productivity usually occurred at 3-5 m and ranged from 5 mg $C \cdot m^{-3} \cdot hr^{-1}$ to 75 mg $C \cdot m^{-3} \cdot hr^{-1}$ at the outer bay, 140 mg $C \cdot m^{-3} \cdot hr^{-1}$ at Boulder Basin and 50 mg $C \cdot m^{-3} \cdot hr^{-1}$ at Hoover Dam in late summer. Since the productivity was lower, light extinction was also reduced (Table 4.6.1), and the depth of the euphotic zone was greater at these stations than in the middle and inner bay. The productivity at 15 m was low (1 mg $C \cdot m^{-3} \cdot hr^{-1}$) for most of the year, but, in mid-summer, increased to about 2 mg $C \cdot m^{-3} \cdot hr^{-1}$ at these stations. The productivity curves for the Outer Las Vegas Bay, Boulder Basin and Hoover Dam were similar to those in the Upper Basin from April to July (Fig. 4.5.3). During the rest of the year, and particularly in August and September, the rates of productivity were higher, and the depth of the euphotic zone was lower, in the Lower Basin. These differences were caused primarily by changes in fertility of the two basins due to nitrogen and phosphorus loading from Las Vegas Wash (Paulson and Baker 1979a). The relationship of nutrients to productivity in each basin is discussed in detail in section 4.7.1.

4.6.2 Lake-Mohave

As in Lake Mead, there was considerable variation in the productivity curves in Lake Mohave. This was related to distribution of Colorado River inflow and changes in fertility that this produced in the reservoir. However, the silt load from discharge at Hoover Dam was low, and therefore, did not have an appreciable effect on vertical productivity in Lake Mohave.

LAKE MOHAVE

PHYTOPLANKTON PRODUCTIVITY
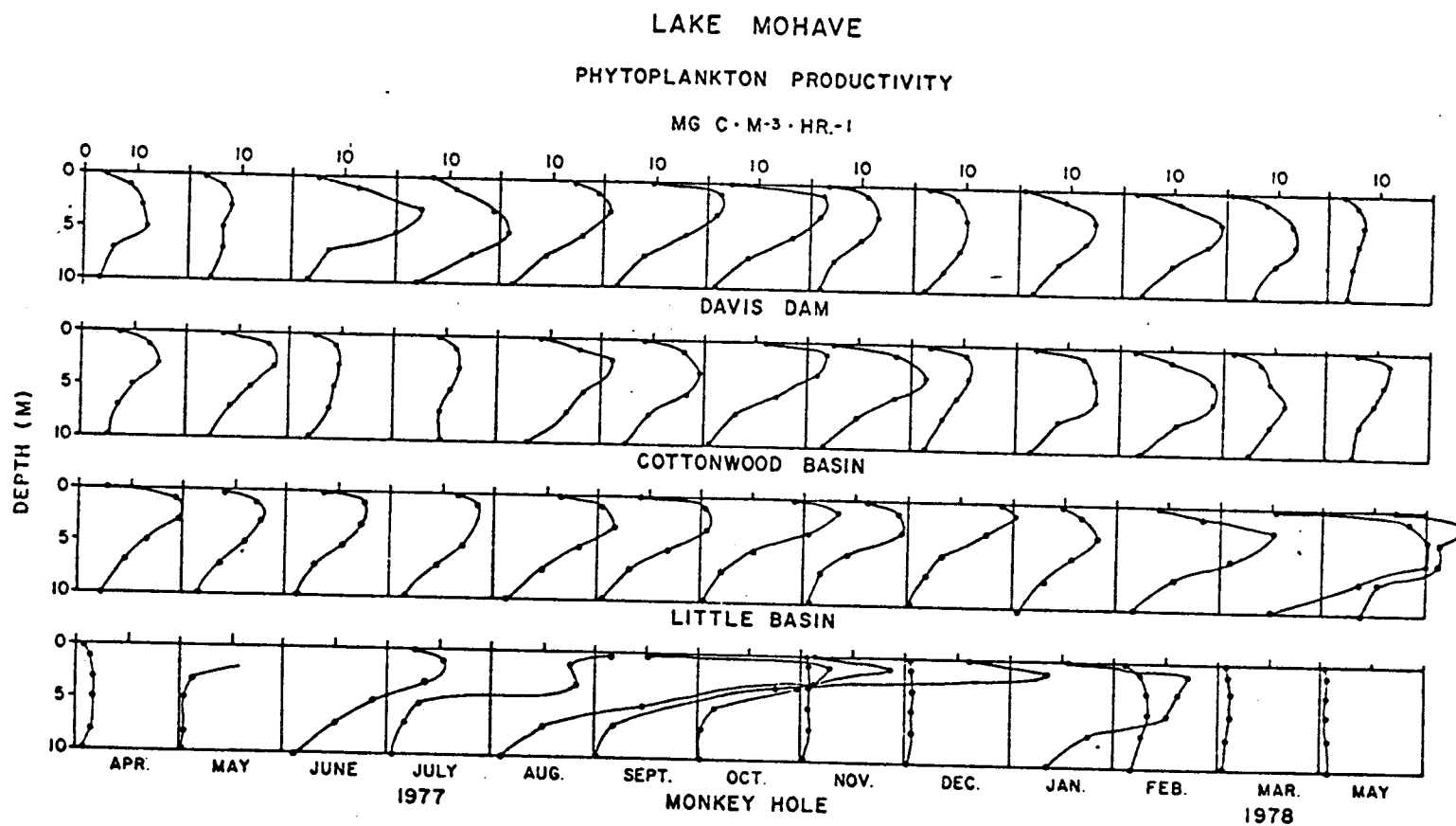
MG C · M-3 · HR.-1

Figure 4.6.4 Phytoplankton productivity profiles in
Lake Mohave.

Productivity at Monkey Hole was very low, ranging from 0.1-3.8 mg $C \cdot m^{-3} \cdot hr^{-1}$ and uniform with depth throughout the year (Fig. 4.6.4). This station was located in the main river, and phytoplankton abundance was low due to cold water temperature and high flushing. Typically, phytoplankton productivity in fast flowing water is low with periphyton and macrophyte productivity being of greater importance. This has been shown for the river section below Hoover Dam (Priscu 1978) where periphyton productivity was about 9 times greater than phytoplankton productivity.

The greatest seasonal variation in productivity occurred at Eldorado Canyon. In winter and early spring, productivity was low (less than 3 mg $C \cdot m^{-3} \cdot hr^{-1}$) and essentially uniform vertically, except in February when productivity increased to a maximum of 36 mg $C \cdot m^{-3} \cdot hr^{-1}$ (Fig. 4.6.4). These low, uniform, productivity curves were similar to those at Monkey Hole and developed because of the lotic conditions at Eldorado Canyon during the winter. Discharge from Hoover Dam was very low in January and February and productivity at Eldorado Canyon increased during this period because of decreased current velocities and less flushing of the resident phytoplankton populations. Productivity in the summer-fall (May-October) was high and ranged from 30-264 mg $C \cdot m^{-3} \cdot hr^{-1}$ at the surface or 1 m. Productivity decreased very rapidly below 5 m because high phytoplankton biomass developed near the surface water and reduced light penetration and the depth of the euphotic zone. This produced productivity curves typical of fertile or eutrophic conditions. At this time thermal stratification was well established at Eldorado Canyon and the river flowed into the hypolimnion. This produced up-lake flow of surface water which allowed phytoplankton populations to become established at high density near the convergence of river-and lake-water. Productivity was also high

because of high nutrient concentrations which occurred as a result of greater mixing at the convergence near Eldorado Canyon. The extremely high productivity near the surface on 30 May, 1977 occurred when the convergence was located just above the canyon and reflects the high fertility of the river-water.

The productivity curves were very similar at the other stations in Lake Mohave. Maximum productivity of 10-20 mg $C \cdot m^{-3} \cdot hr^{-1}$ occurred between 1 and 5 m (Fig. 4.6.4). Productivity gradually decreased below 5 m to less than 4 mg $C \cdot m^{-3} \cdot hr^{-1}$ at 10 m. Productivity at Little Basin was generally higher than at the other stations because of higher nutrient concentration. In the spring of 1978, productivity at Little Basin reached 30-40 mg $C \cdot m^{-3} \cdot hr^{-1}$. Seasonally, the highest maximum productivity occurred in the fall (September-October) at Davis Dam and Cottonwood Basin and early spring (February-May) at Little Basin.

4.7 Spatial and Seasonal Distribution of Phytoplankton Productivity and Relationship to Inorganic Nutrients

4.7.1 Lake Mead

Areal phytoplankton productivity (mg $C \cdot m^{-2} \cdot day^{-1}$), or the depth-integrated sum of each unit volume rate in the euphotic zone, varied considerably between and within each basin of Lake Mead. In the Upper Basin, average daily productivity for the year was highest at Iceberg Canyon (Fig. 4.7.1) (Table 4.7.1). Productivity decreased down-lake to Virgin Basin but then increased again at Boulder Canyon (Fig. 4.7.2). Echo Bay and Overton were more productive than Virgin Basin and Temple Bar but less productive than the other stations in the Upper Basin. There was a two-fold increase in productivity between Boulder Canyon and Boulder Basin (Fig. 4.7.3a). The maximum productivity in Lake Mead occurred at

LAKE MEAD

PHYTOPLANKTON PRODUCTIVITY AND NUTRIENT CONCENTRATION.

Figure 4.7.1 Areal phytoplankton productivity and nutrients (0-10m) in the Upper Arm, Lake Mead.

Table 4.7.1. Areal phytoplankton productivity in Lake Mead, October 1977 - September 1978 (mg $c \cdot m^{-2} \cdot day^{-1}$).

Date	Inner Las Vegas Bay	Middle Las Vegas Bay	Outer Las Vegas Bay	Boulder Basin	Hoover Dam	Boulder Canyon	Echo Bay	Overton	Virgin Basin	Temple Bar	South Cove	Iceberg Canyon
												Station
October 1977	1966	2314	997	668	773	-	327	331	313	534	1020	711
November 1977	1979	1562	919	1454	916	284	330	256	290	-	-	-
December 1977	-	-	-	-	-	-	-	-	-	235	441	706
January 1978	1771[a]	692	603	347	349	274	175	170	171	156	287	98
February 1978	215	719	887	866	767	810	323	290	313	228	422	571
March 1978	1789	2706	637	568	969	516	224	245	190	126	251	1193
April 1978	4236	1042	1223	668	868	333	370	511	317	167	650	938
May 1978	1965	1419	1127	1482	1291	617	681	389	600	691	754	677
June 1978	4083	1309	625	877	675	739	691	747	570	547	960	920
July 1978	8264	3927	779	760	894	528	857	755	589	659	575	675
August 1978	8910	6361	4823	2443	2362	1465	1064	1363	931	697	1206	1378
September 1978	4276	3687	5143	4583	2194	868	884	803	726	576	742	200
Annual average (weighted for missing data)	3444	2239	1544	1301	1057	610	519	498	437	417	670	731

a = monthly average

LAKE MEAD

PHYTOPLANKTON PRODUCTIVITY AND NUTRIENT CONCENTRATION

OVERTON

ECHO BAY

VIRGIN BASIN

BOULDER CANYON

Figure 4.7.2   Areal phytoplankton productivity
and nutrients (0-10m) in Overton
Arm and Virgin Basin, Lake Mead.

the Inner Las Vegas Bay, near the inflow from Las Vegas Wash. The productivity decreased progressively from the inner bay to Hoover Dam, which was the least productive station in the Lower Basin (Fig. 4.7.3b).

There was a definite seasonal trend in phytoplankton productivity at all the stations in Lake Mead, except for Iceberg Canyon (Fig. 4.7.1). The productivity there was greater than 600 mg $C \cdot m^{-2} \cdot day^{-1}$ for each month, except in January. However, the low productivity in January did not appear to be part of a natural cycle, but, rather was caused by reduced light penetration from silt, and flushing of resident phytoplankton populations down-lake with high Colorado River inflow during January. Elsewhere in the Upper Basin, phytoplankton productivity was low and fairly constant in late fall and winter, but then increased progressively in the spring and summer to a maximum of 1000 mg $C \cdot m^{-2} \cdot day^{-1}$ in August.

The concentration of nitrate did not change appreciably during the year at Iceberg Canyon or South Cove (Fig. 4.7.1) due to the continual input from the Colorado River. Nitrate decreased from 300 $\mu g \cdot l^{-1}$ during the winter to 140 $\mu g \cdot l^{-1}$ at Temple Bar, 100 $\mu g \cdot l^{-1}$ at Virgin Basin and Echo Bay, 60 $\mu g \cdot l^{-1}$ at Boulder Canyon and 40 $\mu g \cdot l^{-1}$ at Overton in the summer (Fig. 4.7.2). This decrease in nitrate was caused by uptake by phytoplankton at progressively greater distances down-lake from the Colorado River. However, a deficiency of phosphorus, or possibly iron, apparently prevented the phytoplankton from completely exhausting the supply of nitrate in the Upper Basin (Paulson and Baker 1979a).

The concentration of inorganic phosphorus in the Colorado River was usually less than 5 $\mu g \cdot l^{-1}$. In the Upper Arm, phosphorus increased to nearly 10 $\mu g \cdot l^{-1}$ periodically in the winter but then decreased in the spring and remained between 2-4 $\mu g \cdot l^{-1}$ for the rest of the year (Fig. 4.7.1).

LAKE MEAD

PHYTOPLANKTON PRODUCTIVITY AND NUTRIENT CONCENTRATION

MIDDLE LAS VEGAS BAY
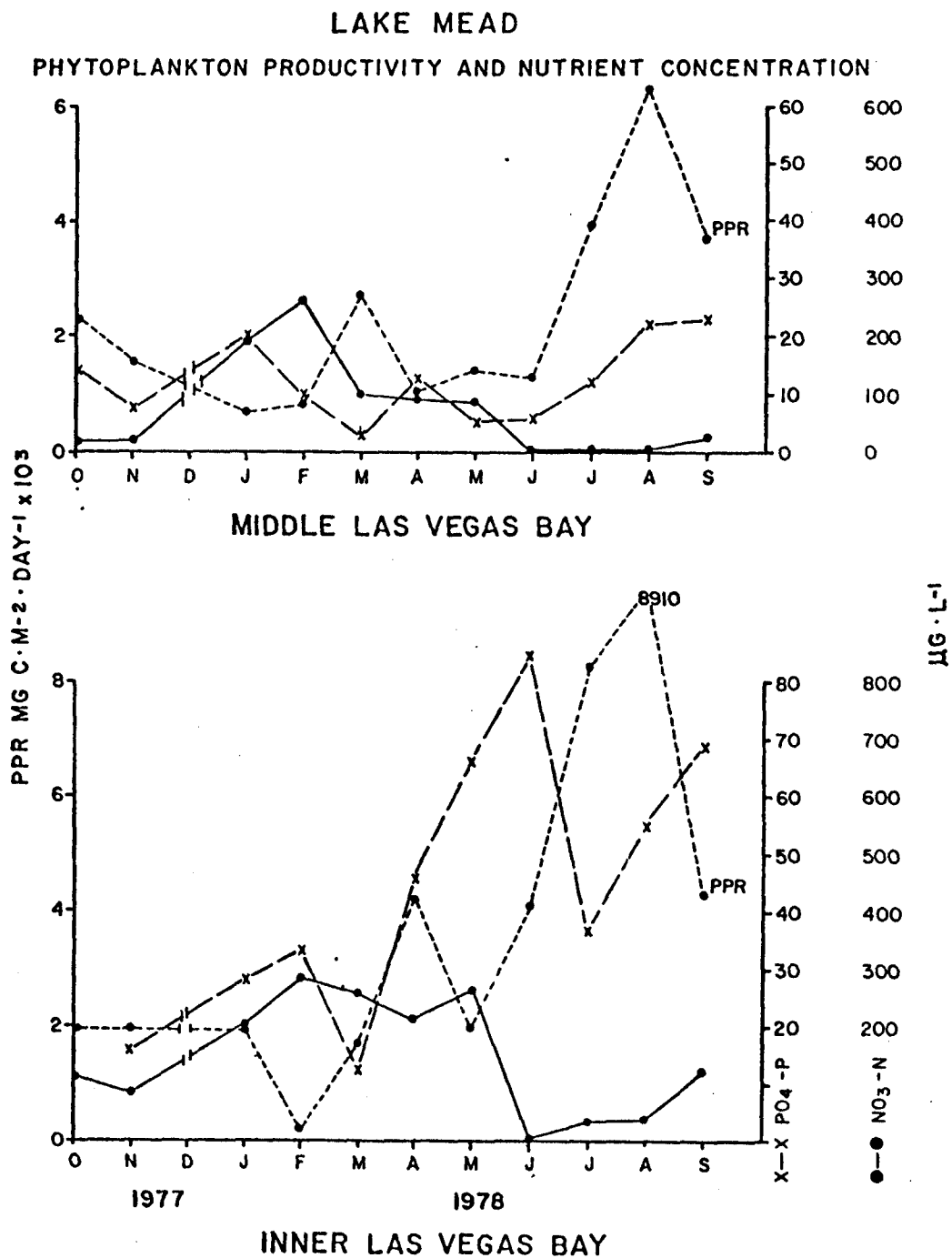
INNER LAS VEGAS BAY

Figure 4.7.3a Areal phytoplankton productivity and nutrients (0-10m) in Las Vegas Bay, Lake Mead.

LAKE MEAD

PHYTOPLANKTON PRODUCTIVITY AND NUTRIENT CONCENTRATION

HOOVER DAM

BOULDER BASIN

OUTER LAS VEGAS BAY
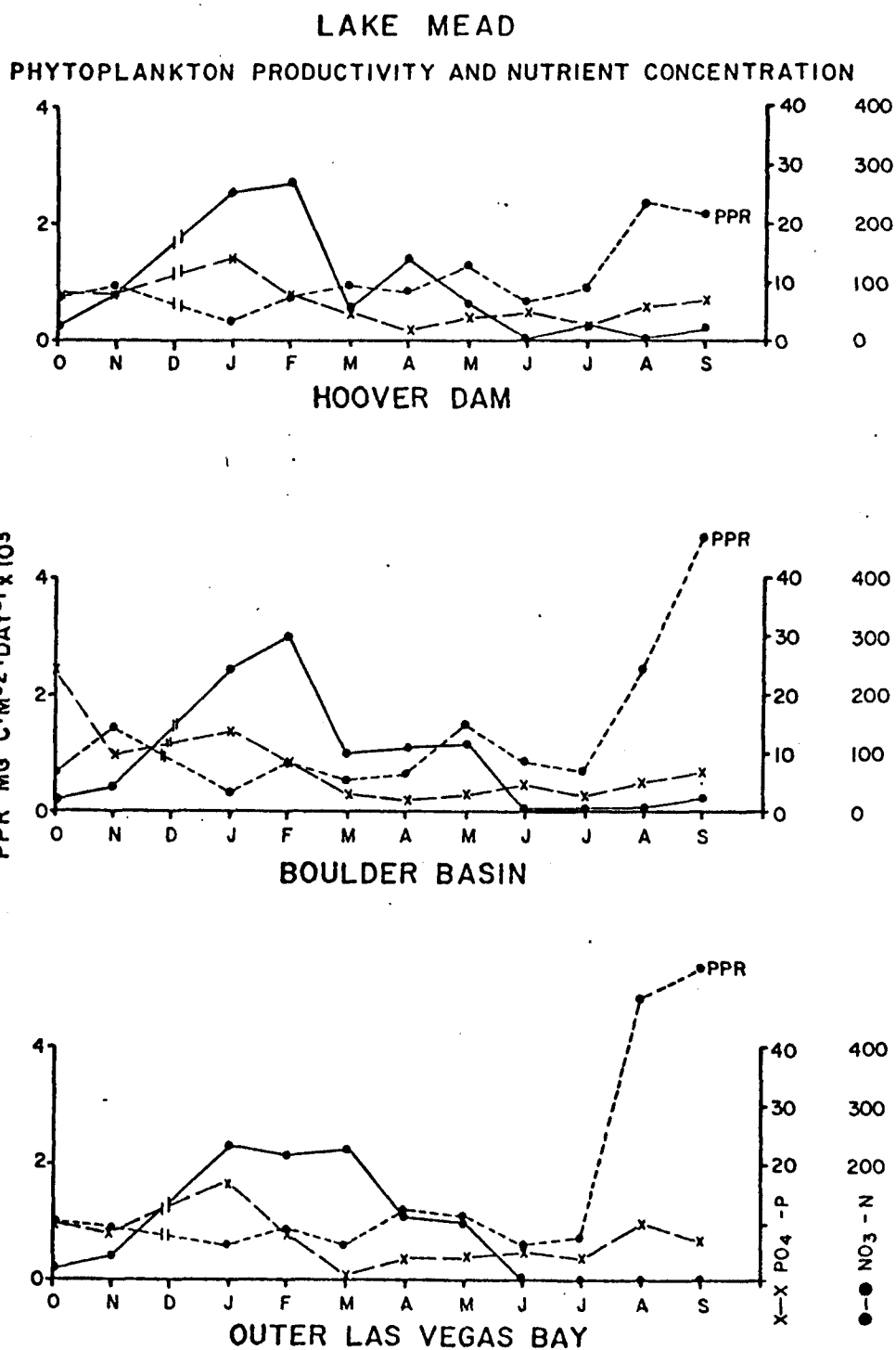
Figure 4.7.3b Areal phytoplankton productivity
and nutrients (0-10m) in Boulder
Basin, Lake Mead.

Phosphorus averaged about 2.5 $\mu g \cdot l^{-1}$ in the rest of the Upper Basin and was virtually constant throughout the year (Fig. 4.7.2). The lack of any appreciable seasonal or down-lake change in phosphorus indicated that it was either being supplied at the same rate as it was being used, or that it was rapidly recycled within the Upper Basin. There was also very little vertical change in phosphorus in the Upper Basin indicating that internal recycling is what maintains the phosphorus pool. The rate of phosphorus recycling, thus, becomes an important factor in regulating productivity in the Upper Basin. This could be expected to vary in relation to temperature, and, indeed, the seasonal changes in productivity do generally follow the annual temperature cycle. Thus, accelerated phosphorus recycling with increasing lake temperature may be part of the reason for the gradual increase in productivity over the spring and summer in the Upper Basin.

There were also significant seasonal trends in areal phytoplankton productivity in the Lower Basin, but these were somewhat different than in the Upper Basin. The lowest productivity still occurred in the winter, and there was a general increase during the spring throughout the Lower Basin (Figs. 4.7.3a,b). However, unlike the Upper Basin, the productivity decreased in June and July but then increased sharply in August and September at the Outer Las Vegas Bay, Boulder Basin and Hoover Dam (Figs. 4.7.3a,b). The productivity pattern was similar to this at the Inner and Middle Las Vegas Bay, except that here the productivity increased in July and August but then decreased significantly in September (Figs. 4.7.3a,b).

The concentration of nitrate also changed considerably over the year in the Lower Basin. Nitrate was fairly low in the fall (20-40 $\mu g \cdot l^{-1}$) but increased to a maximum of 250-300 $\mu g \cdot l^{-1}$ in the winter (Figs. 4.7.3a,b).

Nitrate was reduced to undetectable levels (5 $\mu g \cdot l^{-1}$) by June and, except

for the Inner Las Vegas Bay, remained near this level throughout the

summer. Inorganic phosphorus ranged from 15-20 $\mu g \cdot l^{-1}$ during the winter

at the Outer Las Vegas Bay, Boulder Basin and Hoover Dam, but was reduced

to about 2 $\mu g \cdot l^{-1}$ by March. Phosphorus then increased again to between 7

and 10 $\mu g \cdot l^{-1}$ by late summer (Fig. 4.7.3b). The phosphorus concentration

was 20 $\mu g \cdot l^{-1}$ at the Middle Las Vegas Bay in the winter (Fig. 4.7.3a) but

was reduced to 2 $\mu g \cdot l^{-1}$ in March, followed by an increase to 23 $\mu g \cdot l^{-1}$ in

September (Fig. 4.7.3a). Similarly, at the Inner Las Vegas Bay, phosphorus

increased from a minimum of 12 $\mu g \cdot l^{-1}$ in March to a maximum of 85 $\mu g \cdot l^{-1}$

in June (Fig. 4.7.3a). However, this was followed by a decrease in July and

then an increase again in August and September (Fig. 4.7.3a). In contrast

to the Upper Basin, there were significant seasonal and spatial changes in

phosphorus concentration in the Lower Basin. These were caused primarily

by the phosphorus loading from Las Vegas Wash.

4.7.2 Lake Mohave

Areal phytoplankton productivity ranged from 21-2976 mg

$C \cdot m^{-2} \cdot day^{-1}$ from April 1977 through May 1978 in Lake Mohave (Fig. 4.7.4)

(Table 4.7.2). The lowest productivity was at Monkey Hole which was

characterized by cold water temperatures, high currents, and low

phytoplankton biomass, typical of river-like conditions. A general

seasonal pattern in productivity was evident at the other stations.

Productivity was high over the spring-summer period (March - September)

then declined in the fall (October - November) and remained low during

the winter (Fig. 4.7.4). A small winter peak occurred at Eldorado Canyon

on 3 February, 1978, but that was the only exception to this general

seasonal pattern in productivity.

LAKE MOHAVE
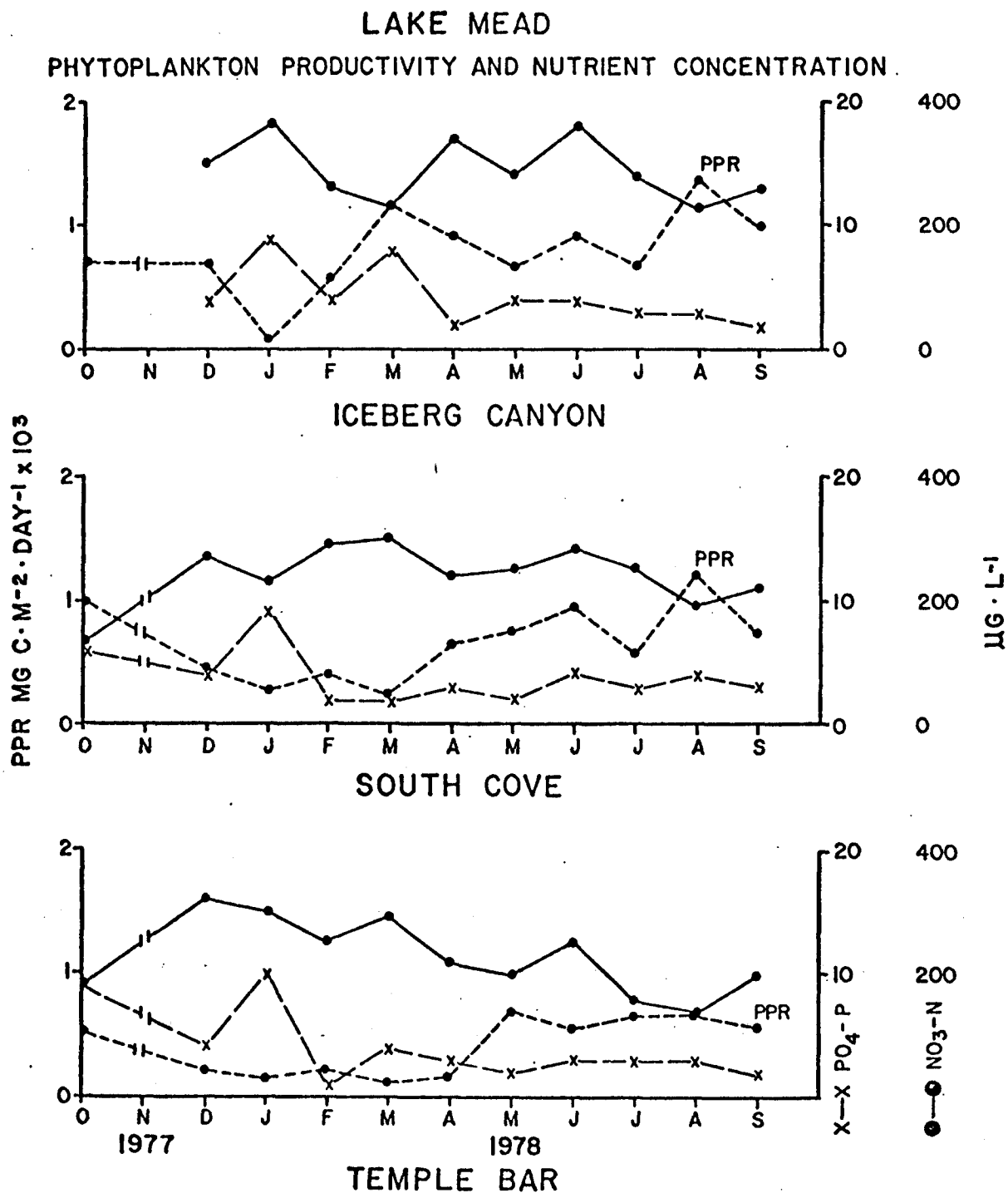
PHYTOPLANKTON PRODUCTIVITY AND NUTRIENT CONCENTRATIONS
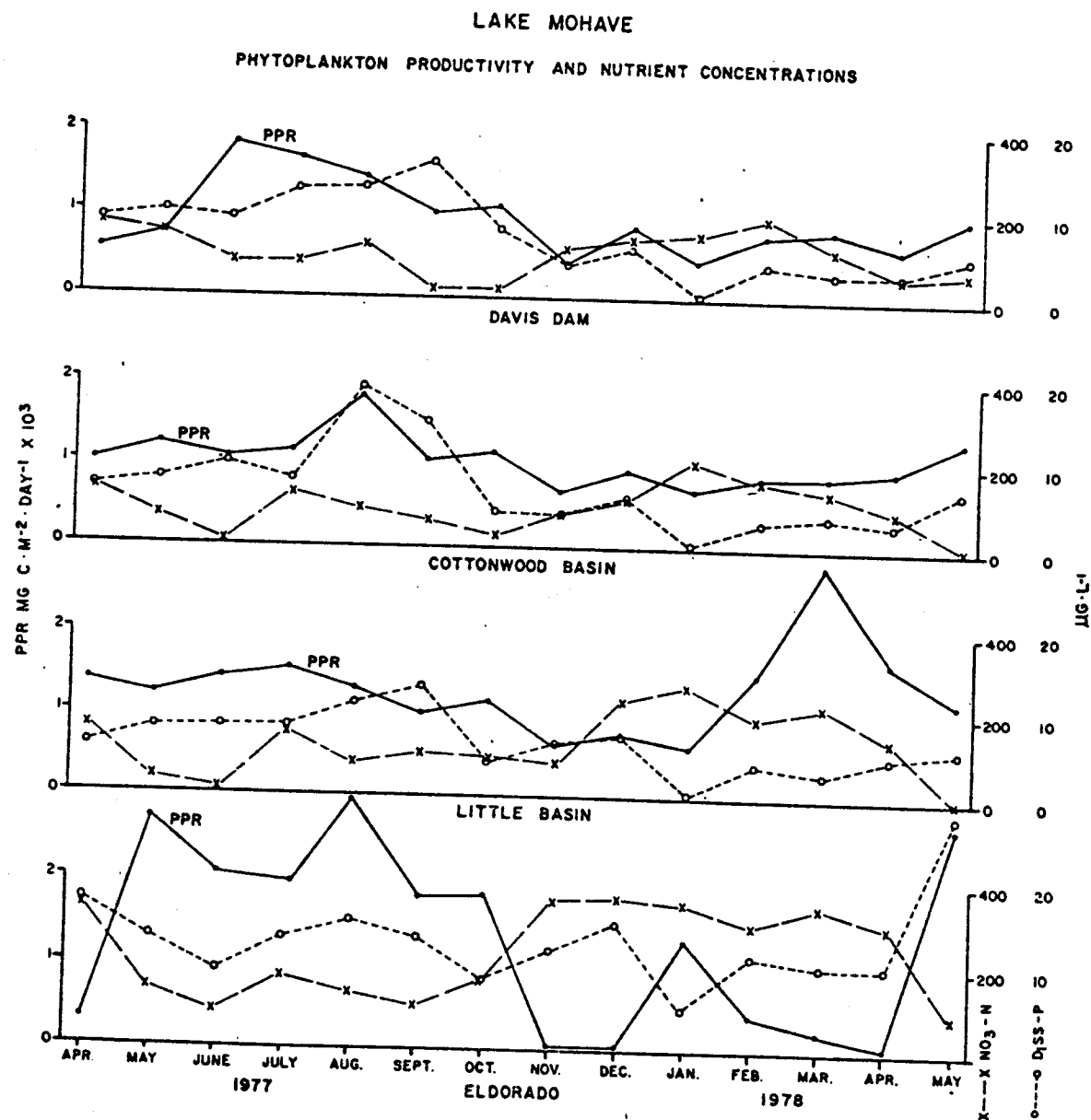
Figure 4.7.4   Areal phytoplankton productivity and nutrients
(0-10m) in Lake Mohave.

Table 4.7.2.   Areal Phytoplankton Productivity in Lake Mohave,

April 1977 - May 1978 (mg $C \cdot m^{-2} \cdot day^{-1}$)

	Stations				
Date	Davis Dam	Cottonwood Basin	Little Basin	Eldorado Canyon	Monkey Hole
29 April 1977				293	315
30 April 1977	571	1027	1357		
11 May 1977				2768	150
12 May 1977	456	713	669		
29 May 1977				2782	104
30 May 1977	1050	1699	1695		
14 June 1977.				2047	234
15 June 1977	1813	1058	1416		
29 July 1977				1974	166
30 July 1977	1644	1142	1537		
10 August 1977			1332		
25 August 1977				2976	96
26 August 1977	1432	1795			
21 September 1977				1806	68
22 September 1977	1000	1070	998		
12 October 1977	1110	1163	1154		
13 October 1977				1828	77
9 November 1977				83	15
10 November 1977	407	710	667		
14 December 1977				59	28
15 December 1977	842	938	738		

periods of the study.

4.8 Spatial and Seasonal Distribution of Chlorophyll-a

4.8.1 Lake Mead

Annual, average chlorophyll-a, like average daily phyto-plankton productivity, varied considerably within and between each basin of Lake Mead. Iceberg Canyon had the highest chlorophyll-a concentration in the Upper Basin (Table 4.8.1). Chlorophyll-a decreased down-lake to Virgin Basin and Echo Bay but then increased slightly at Overton and Boulder Canyon. There was a two-fold increase in chlorophyll-a between Boulder Canyon and Boulder Basin. Chlorophyll-a was higher at the Inner Las Vegas Bay than the rest of Lake Mead, but there was a progressive decrease in chlorophyll-a from the inner bay to Hoover Dam. Thus, as an annual average, the spatial distribution of chlorophyll was similar to that for phytoplankton productivity. However, the seasonal distribution of chlorophyll-a was generally not closely related to productivity.

Phytoplankton productivity was similar at the main-reservoir stations in the Upper Basin and increased steadily from April to August. Chlorophyll-a, however, decreased at some stations and increased at others over this period (Table 4.8.1). In the Lower Basin, there was usually a gradient in produc-tivity from the Inner Las Vegas Bay to Hoover Dam but frequently little difference in chlorophyll-a concentration. Only in late summer, was there a good relationship between productivity and chlorophyll-a in the Lower Basin. Chlorophyll-a increased in July in the inner bay and in August throughout the Lower Basin. By September, chlorophyll-a had decreased at the inner and middle bay, remained the same at the outer bay and increased slightly at Boulder Basin and Hoover Dam. These patterns were closely related to changes in productivity during these periods. But, otherwise,

Table 4.8.1. Chlorophyll-a concentration ($\mu g \cdot \ell^{-1}$) in Lake Mead, October 1977 - September 1978 (from integrated sample of 0, 3, 5 m).

	Station											
	Inner Las Vegas Bay	Middle Las Vegas Bay	Outer Las Vegas Bay	Boulder Basin	Hoover Dam	Boulder Canyon	Echo Bay	Overton	Virgin Basin	Temple Bar	South Cove	Iceberg Canyon
October 1977	6.3	4.9	3.3	5.4	5.2	-	-	-	-	2.2	2.9	3.0
November 1977	9.4	3.3	3.4	3.2	2.2	1.0	0.9	2.5	0.9	-	-	-
December 1977	-	-	-	-	-	-	-	-	0.95	0.9	0.9	1.6
January 1978	16.6[a]	5.3	2.3	2.0	1.3	1.2	0.8	1.0	1.0	-	1.5	2.1
February 1978	1.2	2.5	2.8	2.2	2.7	2.0	0.9	1.6	-	1.2	1.7	2.7
March 1978	3.3	3.8	2.6	1.8	4.6	1.3	0.7	1.1	0.8	0.9	1.0	6.9
April 1978	11.8	1.8	1.2	0.9	1.3	0.6	0.5	0.9	1.7	0.5	1.8	2.5
May 1978	0.3	1.4	1.0	1.1	1.8	1.1	0.9	1.2	1.1	1.3	0.7	1.0
June 1978	3.1	1.2	0.7	-	0.2	0.1	0.5	0.7	0.2	0.1	0.2	0.2
July 1978	16.4[a]	2.1	-	1.4	0.8	0.2	1.0	1.1	0.1	0.6	0.8	1.4
August 1978	23.0	14.0	8.3	5.9	4.4	3.0	0.2	1.3	0.4	2.2	2.0	2.2
September 1978	7.9	6.4	7.9	7.0	6.0	1.4	1.0	0.9	1.8	0.8	0.4	0.6
Annual average (weighted for missing data)	9.4	4.3	3.4	2.9	2.7	1.2	0.8	1.3	0.9	1.1	1.3	2.2

a = monthly average

there was no consistent relationship of these parameters in Lake Mead.

There was a considerable difference in phytoplankton species composition between seasons and locations in Lake Mead (Section 4.11.1). In May, for example, the same phytoplankton species were dominant at no more than two of the ten stations that were examined in Lake Mead. Chlorophyll-a did not change appreciably across the reservoir, but porductivity ranged from 125 mg $C \cdot m^{-2} \cdot day^{-1}$ at Temple Bar to 2075 mg $C \cdot m^{-2} \cdot day^{-1}$ at the Middle Las Vegas Bay. The dominant phytoplankton species at the middle Bay in May was Cryptomonas erosa compared to Microcystis inserta at Temple Bar. Nannoplankton, like Cryptomonas, are noted for their ability to maintain high rates of productivity on a small amount of biomass (chlorophyll-a). Chlorophyll-a content and specific rates of productivity vary widely in relation to size and type of phytoplankton, and the great variation in species composition is apparently the primary reason for the poor relationship between productivity and chlorophyll-a in Lake Mead.

4.8.2 Lake Mohave

There was considerable seasonal variation in chlorophyll-a at each station in Lake Mohave, except Monkey Hole, where chlorophyll-a was low throughout the year (Table 4.8.2). The highest chlorophyll-a concentration in Lake Mohave (49.6 $\mu g \cdot l^{-1}$) occurred at Eldorado Canyon when the cold water-warm water interface was located near this station. This station was low in chlorophyll-a and similar to Monkey Hole in the early spring and winter due to high river-inflow. Chlorophyll-a ranged from 0.8-6.4 $\mu g \cdot l^{-1}$ and averaged 2.8, 2,8 and 3.5 $\mu g \cdot l^{-1}$, respectively, at the down-lake stations. The average daily chlorophyll-a at Eldorado Canyon was 4.6 $\mu g \cdot l^{-1}$ and 2.8 $\mu g \cdot l^{-1}$ with and without the high value recorded on 11 May, 1977.

Table 4.8.2　Chlorophyll-$\underline{a}$ ($\mu g \cdot \ell^{-1}$) in Lake Mohave December 1976 through

May 1978 (from integrated samples at 0, 3, 5 m)

Date	Stations				
	Davis Dam	Cottonwood Basin	Little Basin	Eldorado Canyon	Monkey Hole
December 1976	1.8	1.9	0.1	0.2	
January 1977	3.1	0.1	1.8	4.4	
February 1977	3.2	3.2	3.3	1.5	1.3
March 1977		3.2	3.0	1.4	0.8
April 1977	2.2[a]	2.4[a]	3.2[a]	1.5[a]	1.2[a]
May 1977	2.1[a]	2.6[a]	2.6[a]	26.4[a]	0.4[a]
June 1977	3.0	1.1	2.5	3.2	0.7
July 1977	2.7	1.3	1.2	1.1	0.5
August 1977	1.5	2.4	3.7	5.1	0.8
September 1977	4.8	4.1	3.2	3.4	1.4
October 1977	3.6	2.1	2.9	4.9	0.7
November 1977	3.2	3.4	5.0	3.7	2.0
December 1977	2.3	2.2	6.4		
January 1978*	3.1	3.1	2.9	2.1	1.0
February 1978	4.4	5.2	5.5	2.0	0.7
March 1978	2.6	2.6	4.7	0.4	0.2
April 1978[b]	0.8	1.3	3.4	0.2	1.1
May 1978	2.3	5.3	3.0	5.1	0.1
Average January-December 1977	2.9[c]	2.3	3.2	5.1(3.0[d])	1.0

a - mean monthly value
b - collected 5-6 May 1978
c - weighted for missing data
d - without the high chlorophyll value of 49.6$\mu g \ell^{-1}$ measured on 11 May 1977
* - collected 2-3 February

in the Upper Basin. The Inner Las Vegas Bay was phosphorus limited from January through March (Table 4.9.1), and other stations in the Lower Basin were phosphorus limited from January through May. During the rest of the year, the entire Lower Basin was nitrogen limited. The N:P ratios were usually less than five in the summer and on one occasion decreased to less than 1. The N:P ratio of the Las Vegas Wash inflow averaged about five and never exceeded eight during the study. The high phosphorus input enabled phytoplankton to utilize more inorganic nitrogen in the Lower Basin. This, plus low nitrogen input from the Upper Basin in the summer, created the nitrogen deficiency in the Lower Basin during the summer and fall. The Lower Basin returned to a phosphorus limited state in the winter when the lake mixed and resupplied the epilimnion with nitrate.

4.9.2 Lake Mohave

Inorganic nitrogen to dissolved phosphorus ratios ranged from 222:1 to 3:1 in Lake Mohave (Table 4.9.2). N:P ratios of the nutrient input into Lake Mohave from Hoover Dam was 28:1 indicating phosphorus limitation. At the lake stations, phosphorus limitation was evident for most of the year. N:P ratios did fall below 8:1 at various times at each of these stations from May - October, as nitrate was depleted from the epilimnion by the phytoplankton. These N:P ratios could be considerably lower because both ammonia and nitrate concentrations were at times less than 20 $\mu g \cdot l^{-1}$. However, because this was the minimum detectable level, 20 $\mu g \cdot l^{-1}$ had to be used for purposes of calculating the N:P ratios. The spring-summer increase in the N:P ratios were the result of an increase in both ammonia and nitrate. The increase in ammonia was apparently derived from the ammonification of organic nitrogen. The increase in nitrate may have been from the nitrification of ammonia or

Table 4.9.2   Inorganic nitrogen (NH_3-N+NO_3-N) to dissolved phosphorus (P)

ratios for Lake Mohave from December 1976 to May 1978.   (Computed

from average nutrient concentration at 0, and 10 m in the lake and

0 m at Hoover Dam).

	Station					
Date	Davis Dam	Cottonwood Basin	Little Basin	Eldorado Canyon	Monkey Hole	Below Hoover Dam
December 1976	-	108	96	49	45	38
January 1977	18	14	17	-	-	-
February 1977	11	16	19,23	17	13,53	-
March 1977	-	14	-	20	-	23
April 1977	43,24	57,23	60,31	19,22	19,23	-
May 1977	41,19	30,8	31,8	4,12	23,22	36,24
June 1977	12	4	5	13	19	16
July 1977	13	24	34	16	27	-
August 1977	17	7	9	11	25	26
September 1977	3	7	9	10	25	23
October 1977	6	14	29	24	28	35
November 1977	40	29	18	33	32	33
December 1977	30	27	39	27	38	26
January 1978	-	-	-	-	-	-
February 1978	180,51	225,62	284,52	79,32	44,27	25,29
March 1978	33	38	81	35	37	19
April 1978	-	-	-	-	-	-
May 1978	25[a],14[a]	33,2	36,3	32,3	30,29[a]	30

a = 5, 10 m

from vertical mixing of nitrate in the inflow. The higher N:P ratios

at Eldorado Canyon were caused by partial mixing of river-and lake-water

as the river entered the reservoir.

4.10   Distribution of Dissolved Oxygen

4.10.1   Lake Mead

Typically, the epilimnion of Lake Mead was at saturation

or supersaturated with oxygen because of photosynthetic activity. The

oxygen in the metalimnion was continually reduced during thermal strati-

fication. However, oxygen concentration in the hypolimnion remained higher

than that in the metalimnion, producing a negative heterograde oxygen

profile. The development of the negative heterograde oxygen curve in

1977 and 78 in Hoover Dam (Station 18) is illustrated in Figs. 4.10.1-

4.10.2. Oxygen concentrations were uniform (orthograde) in the winter

when the lake was mixed and isothermal. With the development of

stratification in June and July, there was evident depletion of oxygen

occurring in the metalimnion. This oxygen depletion continued throughout

the summer and fall as the metalimnetic oxygen concentration progressively

decreased with time. In the fall, the depth of the oxygen minimum increased

as mixing occurred to greater depths with the breakdown of thermal

stratification. By January, the negative heterograde oxygen profile was

no longer evident as mixing replenished the oxygen in what were previously

the metalimnion and hypolimnion.

A negative heterograde oxygen profile occurred at all of the stations

in Lake Mead with the exception of the Inner Las Vegas Bay, Overton, and

Iceberg Canyon. Thermal stratification usually did not develop at these

stations, or if it did, the zone of oxygen depletion was close to the

bottom. The most severe metalimnetic oxygen depletion occurred in Las

LAKE MEAD
STATION 18

□ - TEMP

x - OXYGEN

DEPTH (M)

TEMPERATURE/OXYGEN

Figure 4.10.1 Dissolved oxygen and temperature profiles at Hoover Dam, Lake Mead (Jan. 1978 - June 1978).
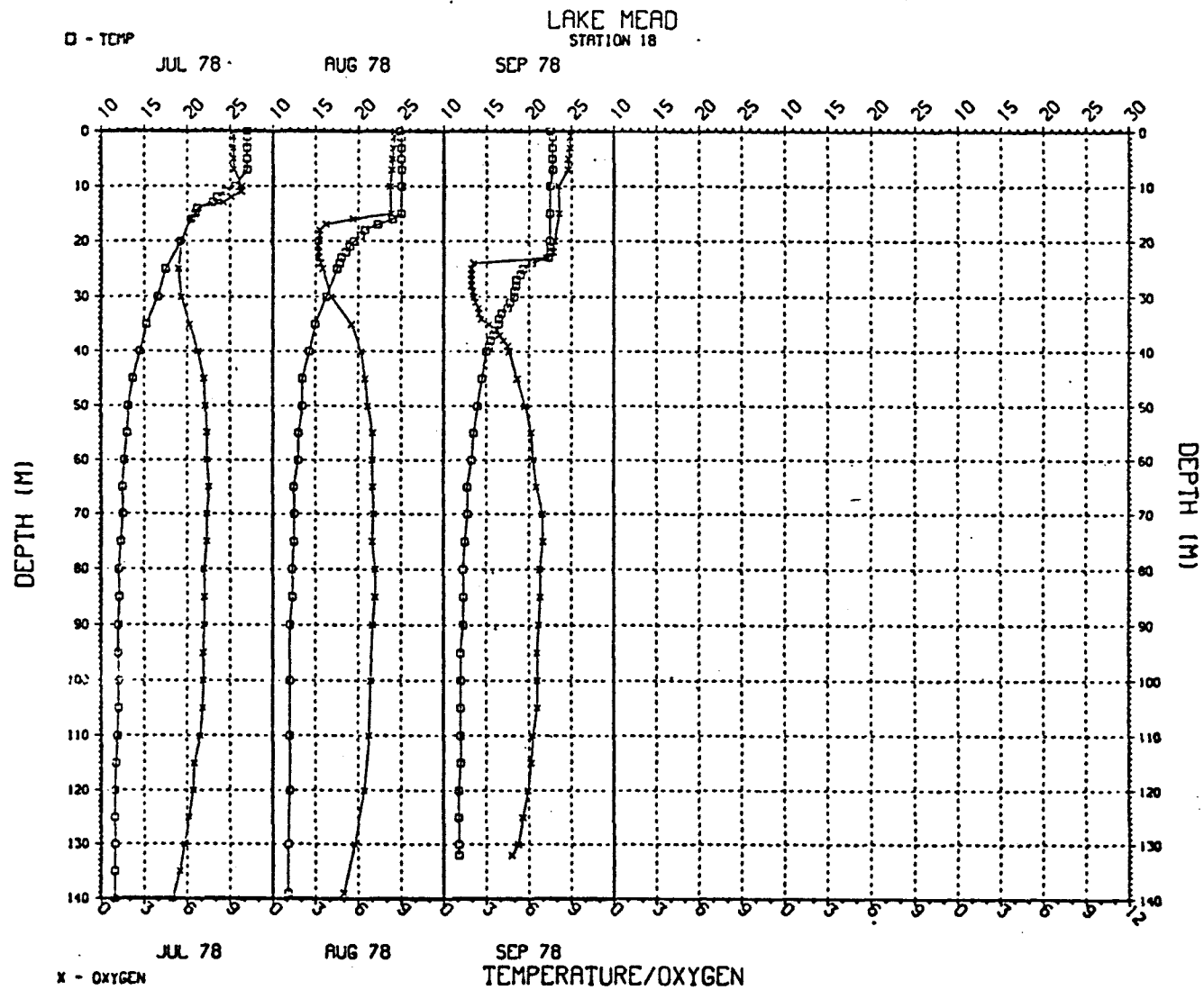
Figure 4.10.2   Dissolved oxygen and temperature profiles at
Hoover Dam, (July 1978 - Sept. 1978).

Vegas Bay where oxygen concentration often fell below 1 mg·l^{-1}. In Boulder Basin, the minimum values were from 2-3 mg·l^{-1}. Oxygen concentrations at stations in the Upper Basin were greater than 5 mg·l^{-1} (Table 4.10.1).

Oxygen measurements taken at Hoover Dam have shown that a negative heterograde oxygen profile has existed ever since the reservoir was formed (unpublished data U.S. Bureau of Reclamation). Midwater oxygen minimums have been related to three possible causes (Shapiro 1960): 1) interposition of water masses having low dissolved oxygen, such as a midwater density flow low in dissolved oxygen or having a higher oxygen demand; 2) horizontal midwater movement of low oxygen water due to sediment uptake from a midwater shelf within the basin; 3) in situ oxygen consumption due to biological and chemical oxygen demand.

The Colorado River does form a midwater flow in Lake Mead but oxygen concentrations are generally high in the Colorado River. If the metalimnetic oxygen minimum was due to a high oxygen demand of the Colorado inflow, oxygen minimums should be more severe in the Upper Basin, which was not the case as the most severe oxygen depletion occurred in Boulder Basin · (Table 4.10.1). Las Vegas Wash forms a midwater flow in Las Vegas Bay and contains sewage effluent which may result in the greater oxygen depletion in the bay. We have no evidence that the Las Vegas Wash density current extended out into the Boulder Basin during the summer, and therefore, the low metalimnetic oxygen minimums at these stations cannot be directly related to the Las Vegas Wash density current. The Colorado River and the Las Vegas Wash inflows may modify or alter oxygen concentrations in the lake, but they are probably not the major cause for the metalimnetic oxygen minimum.

There are also no data to support the hypothesis that the oxygen minimum

able 4.10.1   Minimum Oxygen Concentration in the Metalimnion (10 - 40 m) of
Lake Mead, 1977-1978.

ate	Middle Las Vegas Bay	Outer Las Vegas Bay	Boulder Basin	Hoover Dam	Boulder Canyon	Virgin Basin	Echo Bay	Temple Bar	South Cove
uly 1977	3.0	5.5	6.2	6.1					
ugust 1977	1.9	4.0	3.7	3.8					
eptember 1977	1.1	3.0	3.8	3.2					
ctober 1977	0.8	2.7	2.9	2.8		5.6	5.3	5.5	5.5
ovember 1977	0.7	2.6	2.6	2.5	5.3	5.2	4.9		
uly 1978	2.9	5.0	5.2	5.4	7.1	7.5	6.1	6.1	6.3
ugust 1978	1.1	3.2	3.3	3.5	6.6	6.4	6.2	5.1	5.5
eptember 1978	0.1	1.7	3.2	2.0	5.5	5.5	4.5	5.5	5.5

Station (header spanning data columns)

is due to a midwater shelf. If this were the case, the oxygen minimums would occur at the same lake contour and would not change with lake elevation. The oxygen minimum always develops at the same vertical depth (10-20m) in relation to thermal stratification, regardless of lake elevation, and therefore, is independent of any one particular bottom contour.

In situ oxygen consumption due to biological or chemical demand seems to be the best explanation for the metalimnetic oxygen minimum in Lake Mead. The thermocline represents a sharp density gradient and the settling of organic material produced in the euphotic zone would be greatly reduced as this material encountered the thermocline. This would result in an accumulation of organic matter in the metalimnion which would create an oxygen demand as the material was decomposed. However, mineralization of this organic material primarily in the metalimnion would reduce oxygen demand in the hypolimnion, thereby allowing oxygen to persist in the hypolimnion throughout thermal stratification. Respiration by other organisms which concentrate in the metalimnion, such as zooplankton, could further reduce oxygen in the metalimnion. Burke (1977) has indirectly shown that phytoplankton and zooplankton respiration could account for 57 to 94% of the oxygen utilized in the metalimnion at a station in the Boulder Basin. The oxidation of ammonia (nitrification) excreted by organisms or brought in by inflows may also contribute to the oxygen minimum, but this has not yet been quantified in Lake Mead.

The vertical distribution of pH also showed a negative heterograde profile (Figs. 4.10.3-4.10.4). This corresponds with the oxygen profile and adds support for the hypothesis that the oxygen minimum is caused by in situ oxygen consumption. In the epilimnion, pH values were high
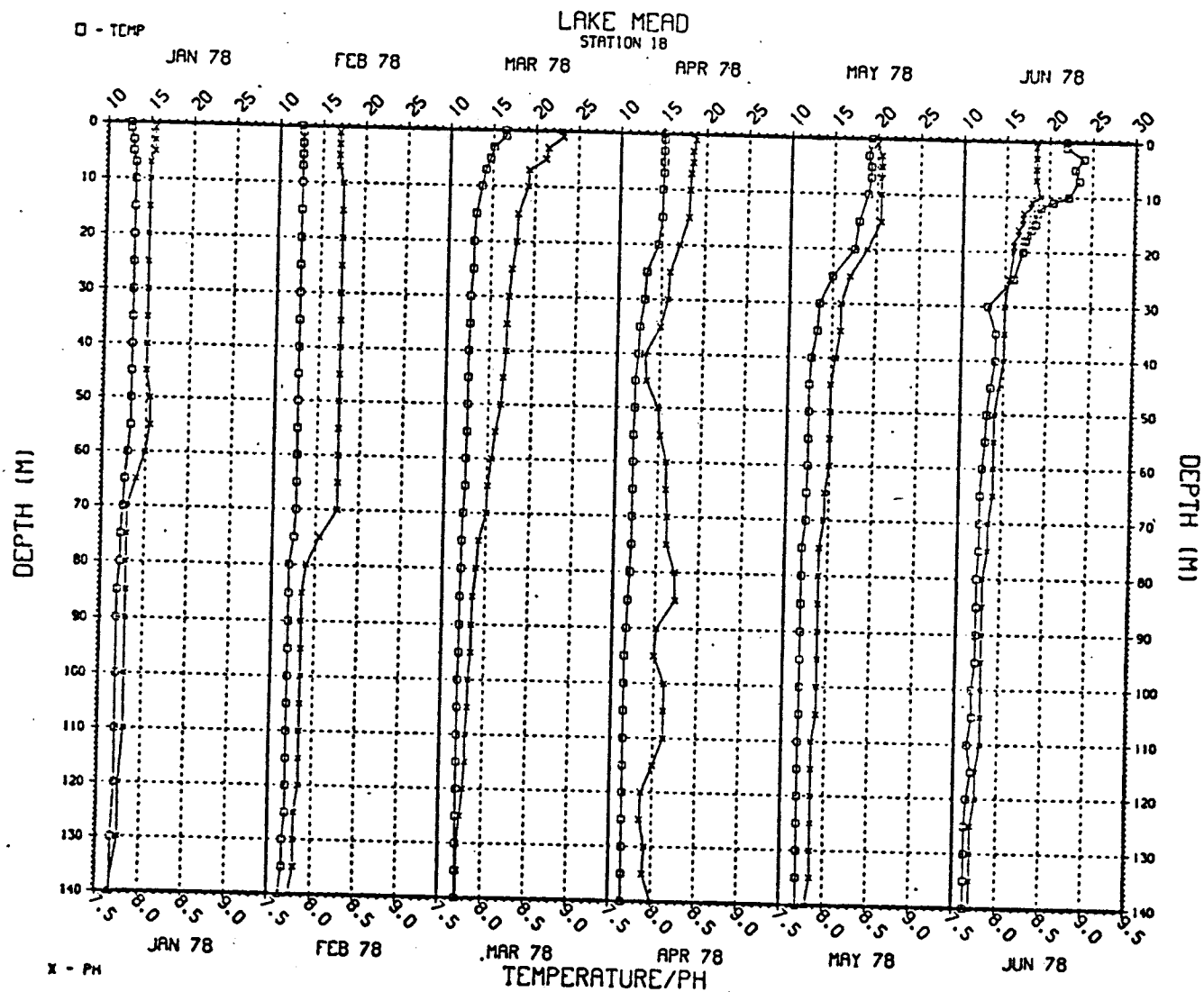
Figure 4.10.3 pH and temperature profiles at Hoover Dam, Lake Mead, (Jan. 1978-June 1978).
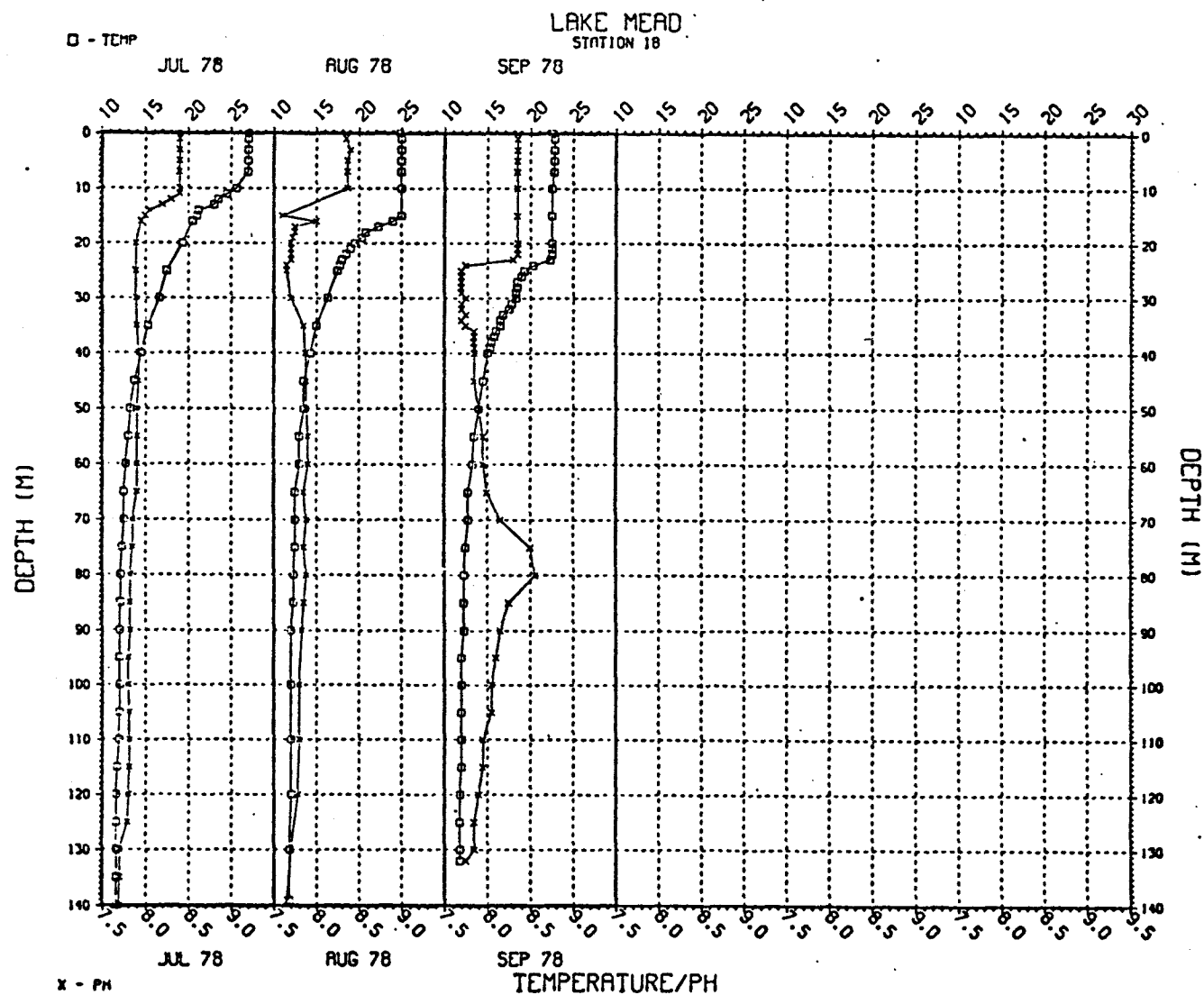
Figure 4.10.4 pH and temperature profiles at Hoover Dam,
Lake Mead (July 1978÷Sept. 1978).

because of release of CO_2 produced by respiration which decreases the pH. The pH in the hypolimnion was higher than in the metalimnion indicating reduced respiratory activity in deep water.

4.10.2 Lake Mohave

There was a slight reduction in oxygen concentration in the hypolimnion of Lake Mohave during thermal stratification (June-October) (Figs. 4.10.5-4.10.6). The lowest oxygen concentration usually occurred at the bottom, resulting in a clinograde oxygen profile. The pH in the hypolimnion decreased in relation to oxygen concentration (Figs. 4.10.7-4.10.8) reflecting biological respiration and mineralization of organic material. However, oxygen concentrations remained relatively high, and were usually greater than 50 percent of saturation (Table 4.10.2). This was especially so at the upstream stations because of the continuous replacement of hypolimnetic water with inflow of highly oxygenated water from discharge at Hoover Dam. There was a general decrease in oxygen concentration in the hypolimnioh at the downstream stations. Davis Dam had the lowest oxygen concentrations in Lake Mohave.

A metalimnetic oxygen minimum usually did not develop in Lake Mohave apparently due to the shallow depth, more turbulent mixing patterns, and continual flushing of the hypolimnion. Also, the thermocline depth was very unstable in Lake Mohave which inhibited long-term accumulation of organic material in the metalimnion.

4.11 Phytoplankton Species Composition

4.11.1 Lake Mead

The phytoplankton community in Lake Mead was very

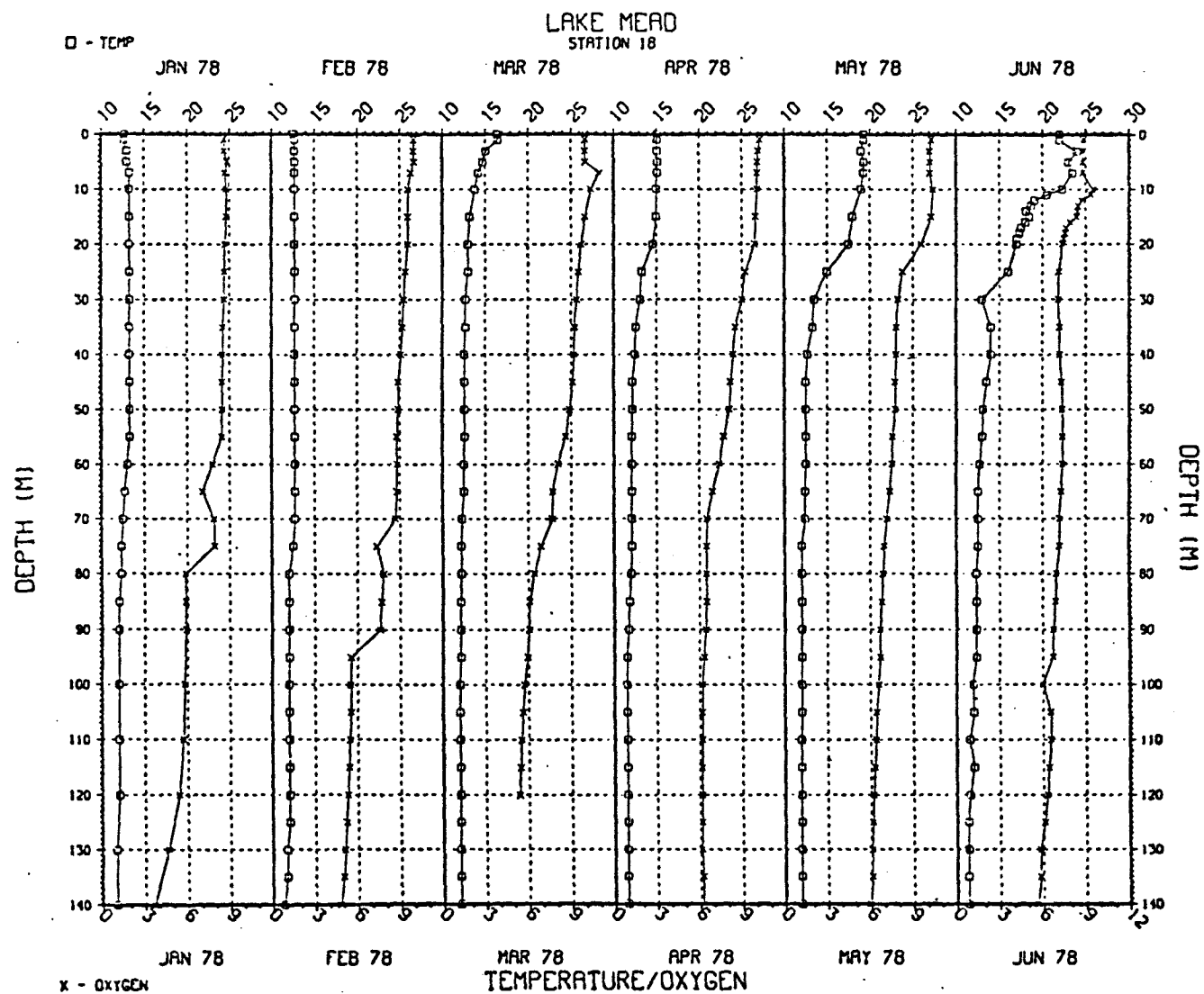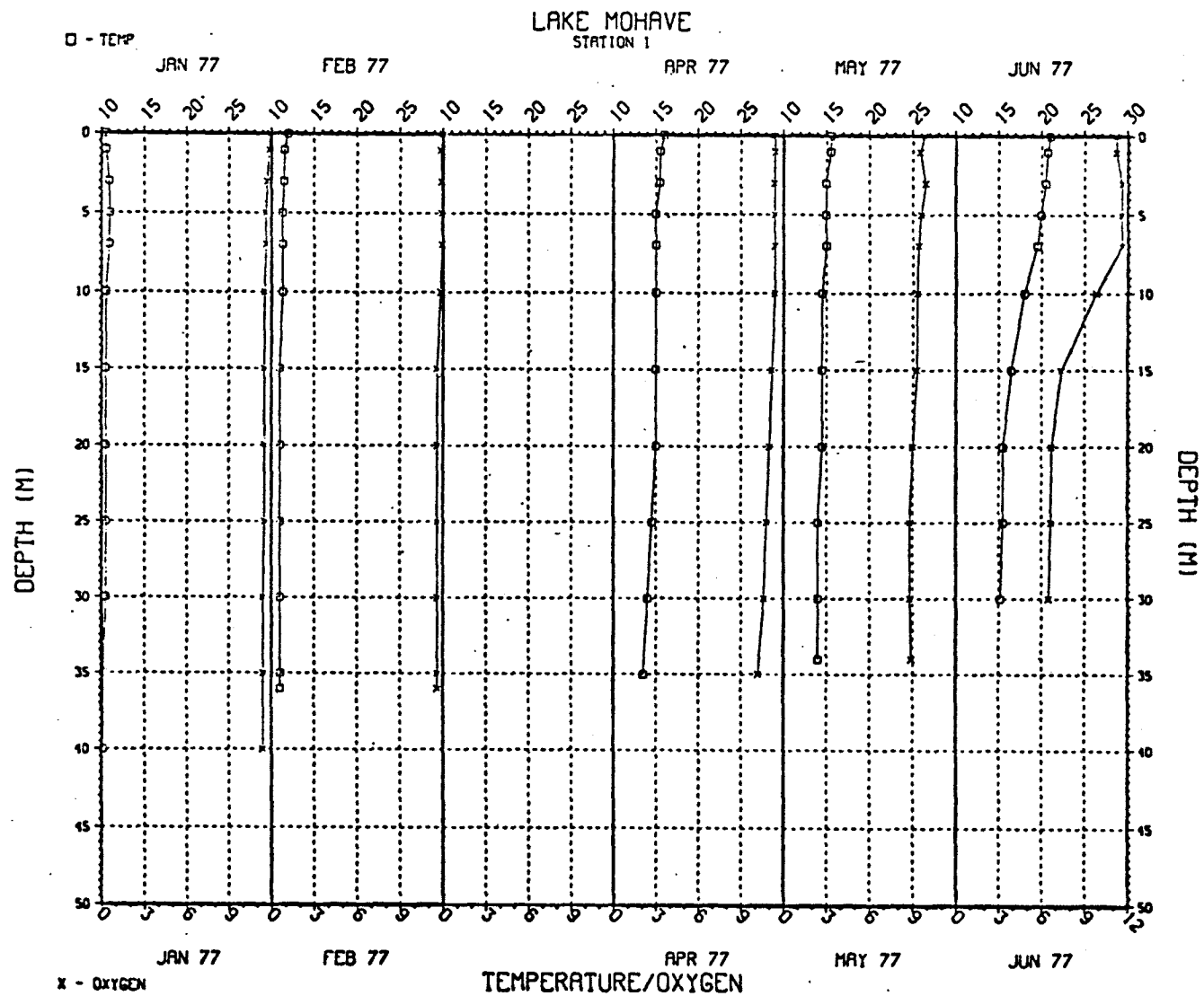Figure 4.10.5 Dissolved oxygen and temperature profiles at
Davis Dam, Lake Mohave, (Jan. 1977-June 1977).
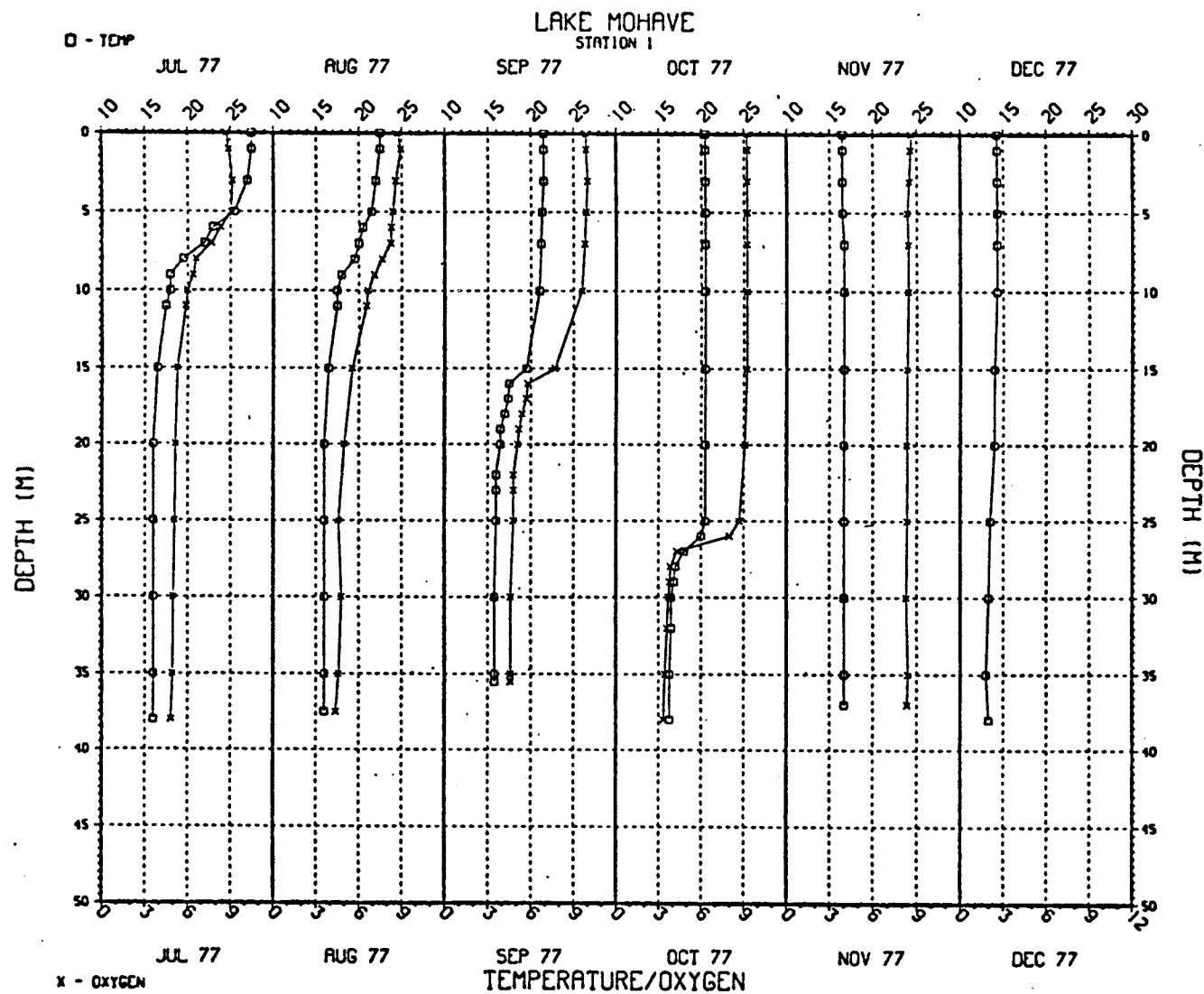
Figure 4.10.6 Dissolved oxygen and temperature profiles at
Davis Dam, Lake Mohave (July 1977-Dec. 1977).
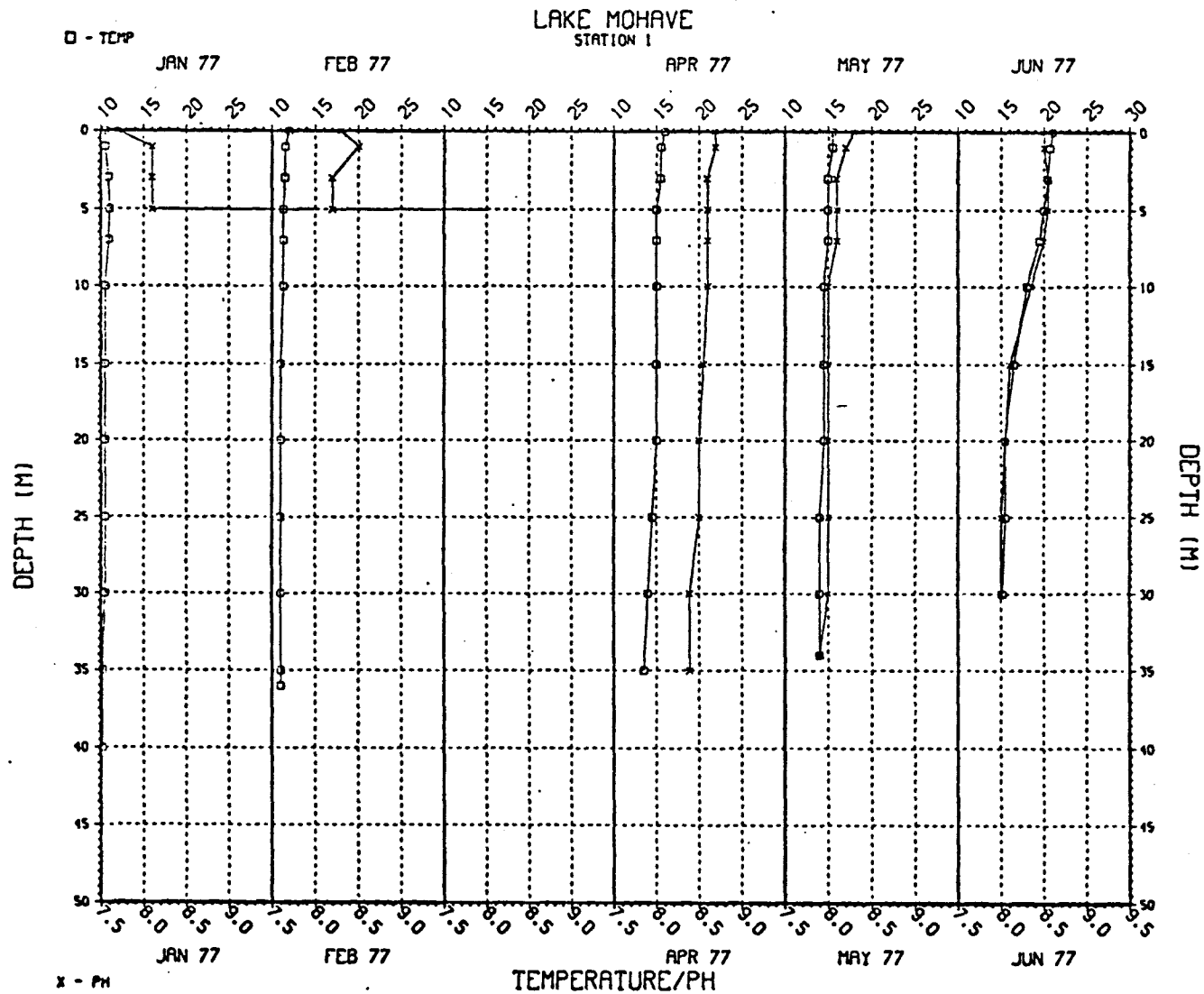
Figure 4.10.7   pH and temperature profiles at Davis Dam,
Lake Mohave (Jan. 1977-June 1977).
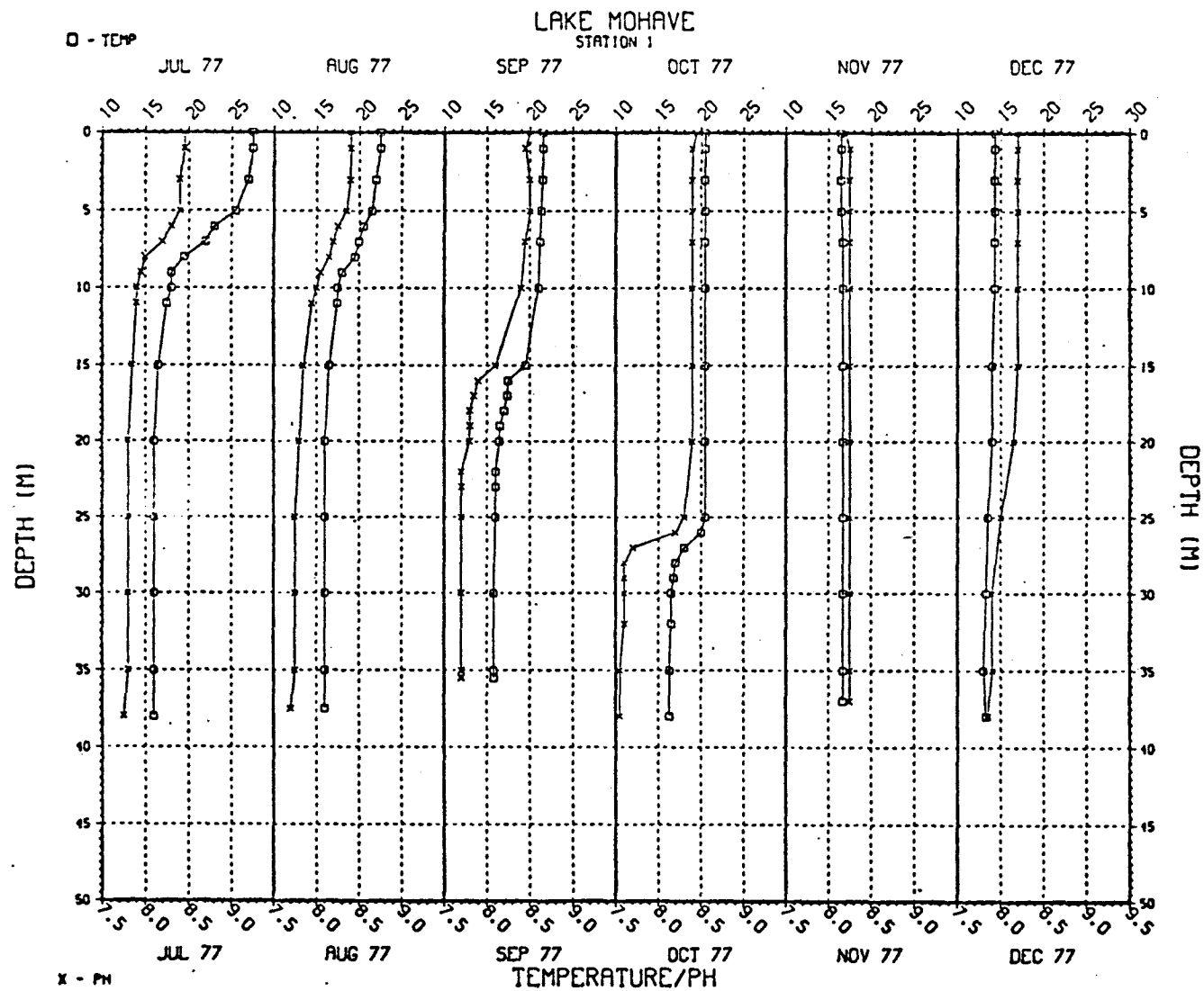
Figure 4.10.8   pH and temperature profiles at Davis Dam, Lake Mohave, (July 1977-Dec. 1977).

Table 4.10.2   Minimum oxygen concentrations in the hypolimnion or just above the bottom in Lake Mohave, 1977.

	STATIONS			
	Davis Dam	Cottonwood Cove	Little Basin	Eldorado Canyon
June	6.5	6.9	7.9	9.6
July	4.9	6.9	8.4	8.5
August	4.4	7.2	8.2	9.5
September	4.6	5.3	5.9	10.0
October	3.4	5.0	8.5	8.3
November	8.4	4.3	6.2	9.0

diverse. A total of 73 genera and 122 species, divided among 6 major phyla, were encountered during the study (Table 4.11.1).

The Chlorophyta were the most diverse group, and included 42% of the total phytoplankton species encountered during the sampling period. The Chlorophyta were present at all locations throughout the year, except for the winter. However, their diversity increased in the summer. During June, July and August, they were the dominant phytoplankton at South Cove, the Overton Arm and Temple Basin. In July, they comprised 30% of the total species present. Chlorella vulgaris was the dominant organism at Boulder Canyon and Lagerheimia was dominant at Temple Bar and South Cove.

The Chrysophyta were the second most diverse group, comprising 22% of the total phytoplankton species in Lake Mead. They were present each month in at least one station. During April and September, they comprised 32% and 22% of the total species, respectively, in Lake Mead. The two most dominant centrate diatoms were Cyclotella and Stephanodiscus.

The Cyanophyta made up 15% of the total phytoplankton species, and they were most common in the late summer and fall. In October and November, 1977 Dactylococcopsis was the dominant organism in the Lower Basin. Anabaenopsis raciborskii appeared in the Lower Basin in July of 1978 and persisted throughout September.

The Cryptophta represented 15% of the total phtoplankton species. The number of cryptomonad species increased in the winter and early spring. Rhodomonas minuta v. nannoplanctica was common throughout the lake in November, 1977 and by January, 1978 it was the dominant organism at all stations in the reservoir.

The Pyrrophyta represented 5% of the total phytoplankton species and they reached a maximum in August. At this time Peridinium, Gymnodinium

Table 4.11.1   Phytoplankton species identified in Lake Mead from
October, 1977 to September, 1978.

PHYLUM CHLOROPHYTA

ORDER CHLOROCOCCALES
Chlorella sp.
Chlorella vulgaris
Coelastrum sp.
Coelastrum reticulatum
Crucigenia quadrata
Echinosphaerella sp.
Echinosphaerella limnetica
Elakatothrix viridis
Franceia sp.
Franceia droescheri
Golenkinia sp.
Golenkinia radiata
Kirchneriella sp.
Lagerheimia sp.
Lagerheimia subsalea
Lagerheimia quadriseta
Oocystis sp.
Oocystis solitaria
Oocystis pusilla
Oocystis borgei
Planktosphaeria sp.
Quadrigula lacustris
Scenedesmus sp.
Scenedesmus bijuga
Scenedesmus dimorphus
Scenedesmus abundans
Scenedesmus quadricauda
Schroederia setigera
Selenastrum sp.
Selenastrum minuta
Sphaerocystis sp.
Sphaerocystis schroeteri

SUB-PHYLUM CHLOROPHYCEAE
ORDER VOLVOCALES
Carteria sp.
Carteria cordiformis
Chlamydomonas sp.
Chlamydomonas globosa
Chlorogonium sp.
Pandorina sp.
Polytoma sp.
Volvox sp.

Table 4.11.1 continued

ORDER TETRASPORALES
Gloeocystis sp.
Gloeocystis planktonica
Gloeocystis vesiculosa
Schizochlamys compacta
Schizochlamys gelatinosa

ORDER ZYGNEMATALES
Cosmarium sp.
Staurastrum sp.

PHYLUM CYANOPHYTA

ORDER CHROOCOCALES
Aphanocapsa sp.
Chroococcus dispersus
Chroococcus dispersus v. minutus
Dactylococcopsis sp.
Gloeocapsa sp.
Gomphosphaeria lacustris
Merismopedia tenuissima

ORDER OSCILLATORIALES
Lyngbya limnetica
Oscillatoria sp.
Oscillatoria limnetica
Oscillatoria planktonica

ORDER NOSTOCALES
Aphanizomenon flos-aquae
Aphanizomenon elachista v. conferta
Aphanizomenon elachista v. planktonica
Anabaena sp.
Anabaena circinalis
Anabaenopsis raciborskii
Anabaenopsis elenkinii

PHYLUM CHRYSOPHYTA

SUB-PHYLUM CHRYSOPHYCEAE
ORDER OCHROMONADALES
Dinobryon sp.
Mallomonas sp.
Ochromonas sp.

ORDER RHIZOCHRYSIDALES
Rhizochrysis sp.

Table 4.11.1 continued

ORDER CHROMULINALES
Chromulina sp.
Chrysococcus sp.
Kephyrion ovala

ORDER PRYMNESIALES
Chrysochromulina parva
Erkenia sp.
Erkenia subaiociliata
Katablepharis ovalis
Rhysolenia sp.

SUB-PHYLUM BACILLARIOPHYCEAE
ORDER CENTRALES
Coscinodiscus sp.
Cyclotella sp. - Cyclotella meneghiniana
Melosira sp.
Melosira granulata
Stephanodiscus sp.

ORDER PENNALES
Achnanthes sp.
Asterionella formosa
Cymbella sp.
Fragilaria crotonensis
Frustulia sp.
Gomphoneis sp.
Navicula sp.
Nitzschia palea
Synedra sp.
Synedra acus

PHYLUM PYRROPHYTA

CLASS DINOPHYCEAE
ORDER GYMNODINIALES
Amphidinium sp.
Ceratium hirundinella
Glenodinium sp.
Glenodinium quadridens
Gymnodinium sp.
Peridinium sp.

PHYLUM CRYPTOPHYTA

CLASS CRYPTOPHYCEAE
ORDER CRYPTOMONADALES
Cryptomonas sp.

Table 4.11.1 continued

        Cryptomonas curvata
        Cryptomonas erosa
        Cryptomonas erosa v. reflexa
        Cryptomonas gracilis
        Cryptomonas marsoneii
        Cryptomonas ovata
        Cryptomonas phaseolus
        Cryptomonas rostrate
        Cryptomonas reflexa
        Chilomonas sp.
        Chilomonas paramaecium
        Chroomonas acuta
        Chroomonas coerulea
        Monomastrix epistheoctyma
        Rhodomonas minuta
        Rhodomonas minuta v. nannoplanctica
        Rhodomonas lacustus

PHYLUM EUGLENOPHYTA

   ORDER EUGLENALES
        Euglena sp.
        Trachelomonas sp.

Ceratium hirundinella and Glenodinium sp. comprised 10% of the population. Peridinum and Ceratium hirundinella were the dominate organisms throughout the year from this group.

The Euglenophyta made up the last 2% of the total phytoplankton genera. They were represented by two species, Euglena and Trachelomonas. Euglena was rather insignificant since it only appeared once in July at Virgin Basin. Trachelomonas appeared sporadically throughout the year.

There was considerable spatial and seasonal variation in the phytoplankton community in Lake Mead. The bluegreen algae, Dactylococcopsis sp. was dominant throughout the Lower Basin in the fall (October-November) (Table 4.11.2). However, Rhodomonas minuta v. nannoplanctica and Chrysochromulina parva were dominant at most stations in the Upper Basin during the fall. In the winter (January-March), these nannoplankton and Cryptomonas erosa were the dominant phytoplankton in most of the reservoir (Table 4.11.2). The greatest spatial variation in the phytoplankton community occurred during the summer. Diatoms, dinoflagellates and green algae were dominant at various times in the Upper Basin (Table 4.11.2). There was no consistent trend at any of these stations in the summer except that Dinobryan was usually dominant at Virgin Basin. Anabaenopsis raciborskii, a nitrogen-fixing bluegreen alga, was the dominant phytoplankton at the Middle Las Vegas Bay in July and throughout the Lower Basin in August. This was replaced by Dactylococcopsis, a non-nitrogen-fixing bluegreen alga, in September.

4.11.2 Lake Mohave

A total of 85 species of phytoplankton were identified in Lake Mohave including 31 Chrysophyta, 26 Chlorophyta, 17 Cyanophyta, 6 Pyrrophyta, 3 Cryptophyta and 2 Euglenophyta (Table 4.11.3). Of the

Table 4.11.2   Dominant phytoplankton species in Lake Mead.

Date	Middle Las Vegas Bay	Boulder Basin	Hoover Dam	Overton	Echo Bay	Boulder Canyon	Virgin Basin	Echo Bay	Boulder Canyon	Virgin Basin	Iceberg Canyon	South Cove	Temple Bar
October 1977	Dactylococcopsis sp. →			→	Rhodomonas minuta v. nannoplanctica →		Cyclotella Rhodomonas minuta v. nannoplanctica	Rhodomonas minuta v. nannoplanctica →		Cyclotella Rhodomonas minuta v. nannoplanctica	Synedra sp.	Chroococcus dispersus v. minuta	Rhodomonas minuta v. nannoplanctica
November 1977	Dactylococcopsis sp. →			Fragilaria crotonensis Rhodomonas minuta v. nannoplanctica	Chrysochromulina parva →			Chrysochromulina parva →				Rhodomonas minuta v. nannoplanctica →	
January 1978	Rhodomonas minuta v. nannoplanctica	Cryptomonas sp.	Navicula sp.	Rhodomonas minuta v. nannoplanctica	Rhodomonas minuta	Rhodomonas minuta v. nannoplanctica →		Rhodomonas minuta	Rhodomonas minuta v. nannoplanctica →				
February 1978	Cryptomonas erosa	Rhodomonas minuta v. nannoplanctica →		→	Chrysochromulina parva	Rhodomonas minuta v. nannoplanctica →		Chrysochromulina parva	Rhodomonas minuta v. nannoplanctica →		Synedra sp.	Chrysochromulina parva
March 1978	Rhodomonas minuta v. nannoplanctica →		Chrysochromulina parva →		Rhodomonas minuta v. nannoplanctica →			Rhodomonas minuta v. nannoplanctica →			Dinobryon sp.	Ceratium hirundinella Rhodomonas minuta v. nannoplanctica	Rhodomonas minuta v. nannoplanctica
April 1978	Rhodomonas minuta v. nannoplanctica →				→			Rhodomonas minuta v. nannoplanctica →		Rhodomonas minuta v. nannoplanctica	Chroomonas caerulea	Rhodomonas minuta v. nannoplanctica	Anabaenopsis sp. Ceratium hirundinella
May 1978	Cryptomonas erosa	Rhodomonas minuta v. nannoplanctica →		Synedra sp.	Rhodomonas minuta v. nannoplanctica →		Chrysochromulina parva	Rhodomonas minuta v. nannoplanctica →		Chrysochromulina parva →		Cryptomonas erosa	Microcystis incerta
June 1978	Chrysochromulina parva →		Navicula sp.	Glenodinium quadridens Dinobryon sp.	Cyclotella Nitzschia palea	Chrysochromulina parva	Dinobryon sp.	Cyclotella Nitzschia palea	Chrysochromulina parva	Dinobryon sp.	Lagerheimia quadriseta	Chrysochromulina parva	Dinobryon sp.
July 1978	Anabaenopsis raciborskii	Lyngbya limnetica	Chrysochromulina parva	Navicula sp.	Rhodomonas minuta v. nannoplanctica Chrysochromulina parva	Chlorella vulgaris	Dinobryon sp.	Rhodomonas minuta v. nannoplanctica Chrysochromulina parva	Chlorella vulgaris	Dinobryon sp.	Trachelomonas sp.	Lagerheimia sp.	Lagerheimia subsalsa
August 1978	Anabaenopsis raciborskii →			Chrysochromulina parva	Ochromonas sp.	Anabaenopsis sp.	Cyclotella sp.	Ochromonas sp.	Anabaenopsis sp.	Cyclotella sp.	Chlorella sp.	Chrysochromulina parva	Cyclotella sp.
September 1978	Dactylococcopsis	Anabaenopsis raciborskii	Dactylococcopsis sp.	Chrysochromulina parva	Peridinium sp.	Cyclotella sp.	Dinobryon sp.	Peridinium sp.	Cyclotella sp.	Dinobryon sp.	Chrysochromulina parva		Rhodomonas minuta v. nannoplanctica

31 species of Chrysophyta, 28 were diatoms. The percentage of chlorophytans was relatively high but they were seldom abundant. Desmids were rarely collected and only 3 species were recorded throughout the study.

There was considerable seasonal periodicity in phytoplankton dominance in Lake Mohave. In the winter, Cryptomonads (Cryptomonas erosa) and diatoms (Cyclotella spp.) dominated the lower three lake stations (Table 4.11.4). These same three stations developed spring (March-May) diatom pulses of Fragilaria crotonensis and in early summer (May-June) were dominated by the bluegreen alga Gomphosphaeria lacustris. In early summer, G. lacustris also became dominant at three lower lake stations. This short-lived early summer pulse of bluegreens was immediately followed by a large dominance of the diatom Synedra delicatissima. The dominance of S. delicatissima lasted throughout the summer and fall at Davis Dam but was disrupted by moderate bluegreen pulses of Raphidiopsis curvata at Little Basin and Cottonwood Basin in September.

Eldorado Canyon and Monkey Hole were quite different in seasonal phytoplankton succession. This resulted mainly from influences of discharge at Hoover Dam. Monkey Hole was almost completely dominated by diatoms throughout the study (Table 4.11.4). The diatoms Navicula tripunctata var. schizonemoides along with Cryptomonas erosa and Oscillatoria sp. were dominant from December to April. A large Cyclotella sp. pulse existed in March and early April. Fragilaria crotonensis and Melosira granulata became abundant in late-April.

In early-May the bluegreen algae Phormidium sp. along with the diatom Cymbella minuta displayed co-dominance at Monkey Hole. Throughout the rest of May and June, Phormidium was the sole dominant organism. Synedra delicatissima was dominant in July but this was replaced by a diverse

Table 4.11.3   Phytoplankton species identified in Lake Mohave from
December, 1976 to September, 1977.

PHYLUM CHLOROPHYTA

    ORDER CHLOROCOCCALES
            Tetraedron minimum v. scrobiculatum
            Sphaerocystis schroeteri
            Akkistrodesmus falcatus v. acicularis
            Lagerheimia ciliata
            Lagerheimia subsala
            Oocystis eremosphaeria
            Oocystis borgei
            Golenkinia radiata v. brevispina
            Botryococcus brawnii
            Dictyosphaerium pulchellum
            Scenedesmus dimorphus
            Scenedesmus bijuga
            Scenedesmus quadricauda
            Scenedesmus abundans
            Scenedesmus intermedius
            Coelastrum microporum
            Pediastrum duplex
            Pediastrum boryanum
            Elakatothrix gelatinosa

    SUB-PHYLUM CHLOROPHYCEAE
    ORDER VOLVOCALES
            Pandorina protuberans
            Pandorina morum
            Carteria klebsii
            Chlamydomonas globosa

    ORDER ZYGNEMATALES
            Staurastrum tetracercum
            Cosmarium sp.
            Closterium sp.

PHYLUM EUGLENOPHYTA

    ORDER EUGLENALES
            Lepocinclis sp.
            Euglena sp.

PHYLUM PYRROPHYTA

    CLASS DINOPHYCEAE
    ORDER GYMNODINIALES
            Gymnodinium fuscum

Table 4.11.3 continued

Gymnodinium aeruginosum
Glenodinium gymodinium v. biscutelliforme
Peridinium quadridens
Ceratium hirundinella

PHYLUM CRYPTOPHYTA

CLASS CRYPTOPHYCEAE
ORDER CRYPTOMONADALES

Chroomonas sp.
Cryptomonas erosa
Cryptomonas marsonii

PHYLUM CHRYSOPHTA

SUB-PHYLUM CHRYSOPHYCEAE
ORDER OCHROMONADALES
Dinobryon divergens
Dinobryon sociale
Mallomonas pseudocoronata

ORDER CENTRALES
*Melosira varians
Melosira granulata
Melosira distans
Stephanodiscus sp.
Cyclotella sp.
Cyclotella meneghiniana

ORDER PENNALES
*Synedra delicatissima
Synedra ulna
*Diatoma vulgare
Diatoma anceps
Diatoma tenue v. elongatum
*Fragilaria leptostauron
Fragilaria crotonensis
Asterionella formosa
Achnanthes lanceolata
*Cocconeis placentula
*Rhoicosphenia curvata
*Navicula tripunctata v. schizonemoides
Navicula cuspidata
Navicula rhynchocephala
Neidium iridis
Gyrosigma sp.

* These genera were also identified in the periphyton community
in the river above Monkey Hole

Table 4.11.3 continued

ORDER PENNALES
   Epithemia sorex
   Cymbella minuta
   Cymbella mexicana
   Cymbella cymbiformis
   Nitzschia vermicularis
   Cymatopleura solea

PHYLUM CYANOPHYTA

ORDER CHROOCOCCALES
   Merismopedia tenuissima
   Chroococcus dispersus
   Gomphosphaeria lacustris
   Microcystis aeruginosa
   Aphanothece sp.
   Coelosphaerium kuetzingianum
   Aphanocapsa sp.
   Coelosphaerium naegelianum

ORDER OSCILLATORIALES
   Oscillatoria limnetica
   Oscillatoria rubescens
   Oscillatoria limosa
   Phormidium sp.
   Spirulina major
   Lyngbya sp.

ORDER NOSTOCALES
   Aphanizomenon flos-aquae
   Anabaenopsis raciborskii
   Raphidiopsis curvata

* These genera were also identified in the periphyton community in the river above Monkey Hole

Table 4.11.4   Dominant phytoplankton species in Lake Mohave, December, 1976 to September, 1977.

Date	Davis Dam	Cottonwood Basin	Little Basin	Eldorado Canyon	Monkey Hole
			Stations		
22-23 Dec.		Cryptomonas erosa	⟶	Navicula tripunctata	Cryptomonas erosa
25 Jan.	Cryptomonas erosa	⟶			
17-18 Feb.	Cryptomonas erosa	⟶		Navicula tripunctata	⟶
21-30 Mar.		Fragilaria crotonensis	Cyclotella	⟶	
16 Apr.	Asterionella formosa	Fragilaria crotonensis	⟶		
29-30 Apr.	Cryptomonas erosa	Fragilaria crotonensis	⟶	Cyclotella	Fragilaria crotonensis
11-12 May	Fragilaria crotonensis	⟶		Chlamydomonas globosa	Phormidium
29-30 May	Fragilaria crotonensis	Gomphosphaeria lacustris	⟶		Navicula tripunctata
14-15 June	Gomphosphaeria lacustris	⟶			Phormidium
29-30 July	Synedra delicatissima	⟶			
25-26 Aug.	Synedra delicatissima	⟶			
21-22 Sept.	Synedra delicatissima	Oscillatoria limnetica	⟶	Raphidiopsis curvata	

community dominated by periphyton species: <u>Melosira</u> <u>varians</u>, <u>Diatoma</u> <u>vulgare</u> and <u>Phormidium</u> sp. in August and September.

The phytoplankton association at Eldorado Canyon displayed characteristics of both lotic and lentic communities, thus reflecting the environmental conditions at this station. In the winter and early spring months (December-April), the community was composed of <u>Cyclotella</u> and <u>Navicula</u> similar to those at Monkey Hole. After thermal stratification, an extremely large bloom of <u>Chlamydomonas</u> <u>globosa</u> developed at Eldorado Canyon. The succession that occurred throughout the rest of the season at this station was similar to that of Little Basin.

4.12 Zooplankton in Lake Mead and Lake Mohave

4.12.1 Community Structure

The zooplankton of Lake Mead and Lake Mohave were well represented by numerous species of Rotifera, Cladocera and Copepoda (Table 4.12.1). Other organisms such as protozoans, ciliates, zooflagellates, and insect larvae were occasionally found, but they were in low numbers and were of minor importance in terms of total zooplankton abundance in these reservoirs. Therefore, this report will be restricted to the major groups of zooplankton.

The zooplankton communities of Lakes Mead and Mohave were very similar and consisted of organisms typical of other waters (Table 4.12.1). Of those genera listed by Pennack (1957) as being most widely distributed in limnetic habitats in North America, <u>Keratella</u>, <u>Polyarthra</u>, <u>Filinia</u>, <u>Kellicottia</u>, <u>Conochilus</u>, <u>Asplanchna</u>, <u>Synchaeta</u> (Rotatoria); <u>Daphnia</u>, <u>Bosmina</u>, <u>Diaphanosoma</u>, <u>Ceriodaphnia</u>, <u>Chydorus</u> (Cladocera); and <u>Cyclops</u>, <u>Mesocyclops</u>, <u>Diaptomus</u> (Copepoda), were all found in Lake Mead, and most were found in Lake Mohave. Williams (1966) reported the rotifer genera <u>Branchionus</u>,

Table 4.12.1   Zooplankton species in Lake Mead and Lake Mohave.

Species	Occurrence	
ROTIFERA		
Asplanchna priodonta (Gosse)		Both
Brachionus calyciflorus (Pallas)	Lake Mead	
B. patulus (Müller)	Lake Mead	
B. quadridentatus (Herman)		Both
Collotheca sp.		Both
Conochilus unicornis (Rousselet)		Both
Dicrarophorus sp.		Both
Euchlanis sp.		Both
Filinia sp.	Lake Mead	
Kellicottia longispina (Kellicott)	Lake Mead	
Keratella cochlearis (Gosse)		Both
K. earlinae (Ahlstrom)		Both
K. quadrata (Müller)		Both
K. valga (Ehrbg)	Lake Mead	
Lecane (Lecans) luna (Müller)		Both
L. (Monostyla) lunaris (Ehrbg)		Both
Lepadella sp.		Both
Monommata sp.	Lake Mead	
Notholca (Müller)		Both
Platygias quadricornis (Ehrbg)	Lake Mead	
Ploeosoma sp.		Both
Polyarthra spp.		Both
Syncheata sp.		Both
Testudinella sp.		Both
Trichocerca spp.		Both
Trichotria sp.		Lake Mohave
Hexarthra sp.	Lake Mead	
Keratella serrulata (Ahlstrom)	Lake Mead	
CLADOCERA		
Macrochaetus sp.	Lake Mead	
Alona guttata (Sais)		Both
A. quadrangularis (Müller)		Both
Alonella acutirostris		Lake Mohave
Bosmina longirostris (Müller)		Both
Ceriodaphnia quadrangula (Müller)		Both
Chydorus sphaericus (Müller)		Both
Daphnia sp. (Scourfield)		Both
D. galeata mendotae (Birge)		Both
D. pulex (leydig)		Both
Diaphanosoma brachyurum (lieven)		Both
Leptodora kindti (Focke)	Lake Mead	
Moina sp.		Both
Scapholeberis kingi (Sars)		Lake Mohave
Ceriodaphnia lacustris (Birge)	Lake Mead	

Table 4.12.1 continued

Polyphemus pediculus (Linne)   Lake Mead

        <u>COPEPODA</u>

Cyclops bicuspidatus thomasi (Forbes)   Both
C. varicans rubellus (Lilljeborg)   Lake Mohave
C. vernalis americanus (Fischer)   Both
Diaptomus clavipes (Schacht)   Both
D. reighardi (Marsh)   Both
D. siciloides (Lilljeborg)   Both
Eucyclops agilis (Kock)   Lake Mead
Macrocyclops albidus (Jurine)   Lake Mead
Mesocyclops edax (Forbes)   Both
Onychocamptus mohammed (Blanchard and Richard)   Both

Keratella, Polyarthra, Synchaeta and Trichocerca to be most widely distributed in the major waterways of the United States, and these genera were also found in both reservoirs.

4.12.2 Seasonal Succession

4.12.2a Rotifers

The seasonal succession of the rotifers in Lake Mead and Lake Mohave was closely related to water temperature, as has been previously reported for other lakes (Moore 1978).

The rotifers were most common in the spring and early summer as water temperature was increasing. The periods of peak abundance for the five most common rotifers in Lake Mead and Lake Mohave are summarized in Table 4.12.2. The periods of peak abundance for each rotifer species were usually the same in both lakes. Variations from this trend were seen in those rotifers which had November peaks in Lake Mead (Collotheca, K. cochlearis, Polyarthra). In Lake Mohave these organisms reach peak abundance during January and February.

Moore (1978) reported that the most important factor influencing the birth rate, hence seasonality, of predaceous rotifers was the availability of prey. Between early and late February 1978, the density of Asplanchna priodonta, a predatory rotifer, decreased sharply in Lake Mohave. During this same time Keratella cochlearis, an important prey item of A. priodonta, also decreased in abundance. Whether the decrease in abundance of K. cochlearis was due to predation or some other cause could not be determined.

4.12.2b Cladocerans

Seasonal successions of the major species of Cladocera in Lake Mead and Lake Mohave (Table 4.12.3) appeared to be influenced by several factors. In the spring months, Daphnia galeata

Table 4.12.2 Periods of peak abundance for the common rotifers in Lake Mead and Lake Mohave. (Period of greatest abundance given first).

Species	Lake Mead		Lake Mohave	
Asplanchna priodonta	April/May	January	January	May
Collotheca	March/April	November/January	May	January
Keratella cochlearis	May/June	November	January/February	April/May
Polyarthra	March/April	November	May	January/February
Synchaeta	March/May	January	April/May	February

mendotae replaced Bosmina longirostris as the dominant cladoceran. According to the Size-Efficiency Hypothesis of Brooks and Dodson (1965), D. galeata should out compete the smaller and, therefore, less efficient B. longirostris. An alternate explanation for this succession is that water temperature at this time favored greater reproduction by D. galeata, allowing their population to increase rapidly. Haney (1973) showed that Daphnia are much more efficient grazers than B. longirostris, while Hall (1964) and Tappa (1965) have shown that temperature is very important in the seasonal cycles of Daphnia species. A combination of both of these factors is probably at work in Lake Mead and Lake Mohave.

D. galeata remained the dominant cladoceran in Lake Mead until April-May when D. pulex became dominant. In Lake Mohave, D. pulex reached its greatest abundance in May. This succession (April-May) coincides with the spawning of threadfin shad Dorosoma petenense, in these lakes (Deacon, Paulson and Minckley 1970). Threadfin shad feed heavily on Daphnia and were shown by Applegate and Mullan (1967) to cause the collapse of Daphnia populations and their subsequent replacement by Bosmina longirostris in Bull Shoals Reservoir. There is some indication in the literature that D. pulex undergoes a deeper vertical migration than D. galeata. If this is so, D. pulex would be favored because it would be less susceptible to predation by shad which occur primarily in the epilimnion and metalimnion of Lake Mead (Deacon and Tew 1973, Paulson and Espinosa 1975). After May, D. galeata again became the most abundant daphnid in Lake Mead, although B. longirostris was the most abundant cladoceran. The final crash of D. galeata populations during June in Lake Mead followed an algal succession from small flagellated cells (Chroomonas and Cryptomonas) to larger filamentous diatoms (Fragilaria and Asterionella) and bluegreen algae

Table 4.12.3   Periods of peak abundance for the common cladocerans in Lake Mead (October 1977-
September 1978) and Lake Mohave (October 1977 - May 1978).

Species	Lake Mead	Lake Mohave
Daphnia galeata mendotae	February - March	March - May
Daphnia pulex	April - May	May
Bosmina longirostris	July - October	July - October

Anabaenopsis). The smaller algae are among those which are best utilized by zooplankton; the latter forms are often not used as food by zooplankton (Porter 1973, 1977).

By July, Bosmina longirostris was the dominant cladoceran in both reservoirs and this succession was most likely caused by shad predation on Daphnia and changes in food availability. In Lake Mohave, B. longirostris remained the dominant cladoceran until spring, when it was again succeeded by D. galeata.

4.12.2c Copepods

Succession of the calanoid copepods in Lake Mead and Lake Mohave (Table 4.12.4) was related to temperature. In Lake Mohave, Diaptomus siciloides was the most abundant calanoid copepod throughout the year, and D. reighardi was never found to be dominant in this lake. In Lake Mead, D. reighardi was the most abundant calanoid early in the year, but in the summer it was succeeded by D. siciloides. D. reighardi was probably the most abundant calanoid in Lake Mead during the early spring because it is better adapted than D. siciloides to the cooler temperatures present at this time. Carter (1974) reported that D. reighardi hatched from resting eggs early in the growing season.

Seasonal successions of the cyclopoid copepods were also related to temperature. Although Cyclops bicuspidatus, C. vernalis and Mesocyclops edax are predaceous, their seasonality did not seem to be dependent upon prey availability. However, the availability of prey may have limited their absolute abundance. C. bicuspidatus was the dominant cyclopoid copepod in Lake Mead from the late fall until early summer but reached maximum abundance in the spring. C. bicuspidatus was succeeded by M. edax in the summer which remained dominant until the fall. These two successions

Table 4.12.4 Periods of peak abundance for the common copepods in Lake Mead (October 1977 –
September 1978) and Lake Mohave (January 1977 – May 1978).

Species	Lake Mead	Lake Mohave
Calanoid Copepods		
Diaptomus siciloides	August – September	April – May
Diaptomus reighardi	March – May	–
Cyclopoid Copepods		
Cyclops bicuspidatus	April – May	March – May
Cyclops vernalis	–	February – May
Mesocyclops edax	August – September	June

occur at the same time as thermal stratification (in the early summer) and fall overturn. In the early summer, as the lake began to stratify, there was a large increase in the numbers of M. edax copepodites. Similarly, in the fall, at the time of overturn, there was a large increase in the numbers of C. bicuspidatus copepodites. Some physical or chemical factor associated with stratification and mixing results in these two copepods encysting (C. bicuspidatus in the early summer, M. edax in the fall) and excysting (fall and early summer, respectively) from diapause. Smyly (1961) found the encystment of M. leuckarti to closely coincide with the time of fall turnover. In Lake Mohave, this same pattern was generally repeated, but C. vernalis was the dominant cyclopoid copepod for a short time in the early spring and was then succeeded by C. bicuspidatus as the dominant cyclopoid for most of the spring. In the early summer, C. bicuspidatus was replaced by M. edax as also occurred in Lake Mead.

4.12.3 Spatial Distribution and Abundance

The spatial distribution of major zooplankton groups was similar throughout Lake Mead except at stations near the inflows (Fig. 4.12.1). The relative abundance of rotifers increased and copepods decreased at Iceberg Canyon, Overton and the Inner Las Vegas Bay. However, there was little variation in the distribution of cladocerans in Lake Mead. In Lake Mohave, the distribution of zooplankton was similar at Davis Dam and Cottonwood Basin (Fig. 4.12.2). However, the rotifers comprised most of the population in Little Basin, but cladocerans were dominant at Eldorado Canyon and copepods at Monkey Hole.

The average abundance of the zooplankton population in Lake Mead decreased from Iceberg Canyon to Boulder Canyon (Fig. 4.12.3). Abundance then increased considerably in the Lower Basin, reaching a maximum at the
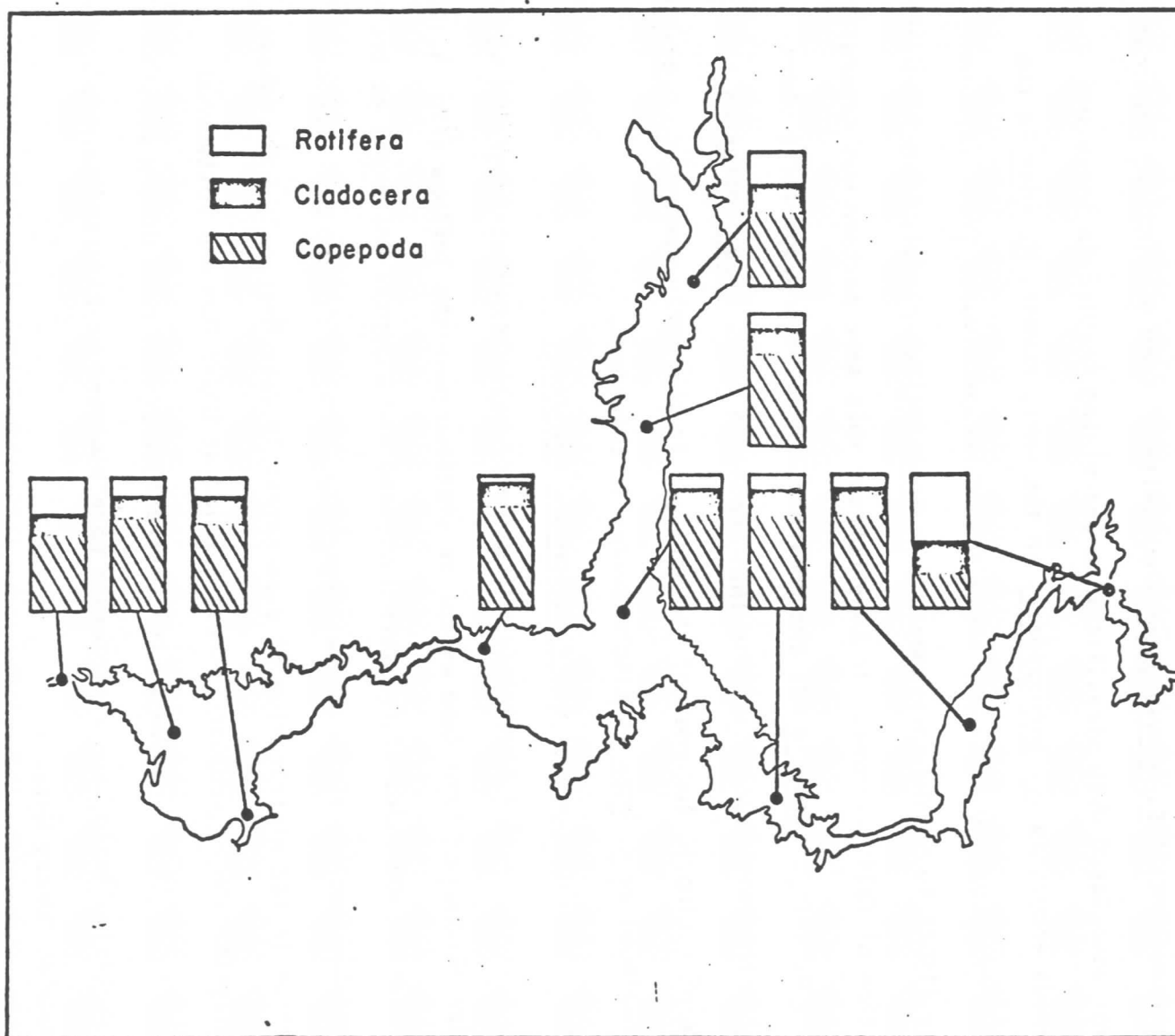
Figure 4.12.1   Spatial distribution of zooplankton in Lake
Mead.
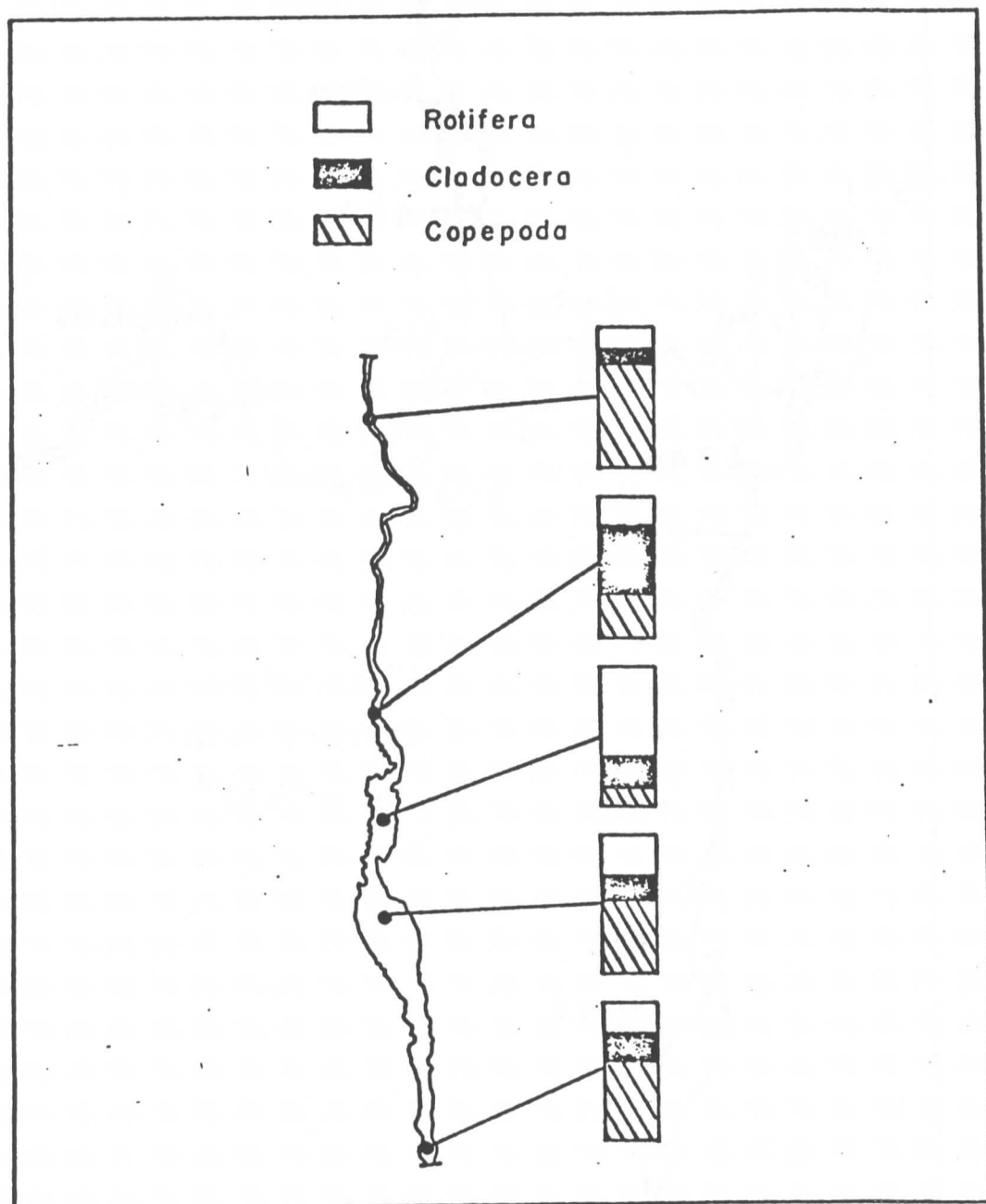
Figure 4.12.2 Spatial distribution of zoo-
plankton in Lake Mohave.
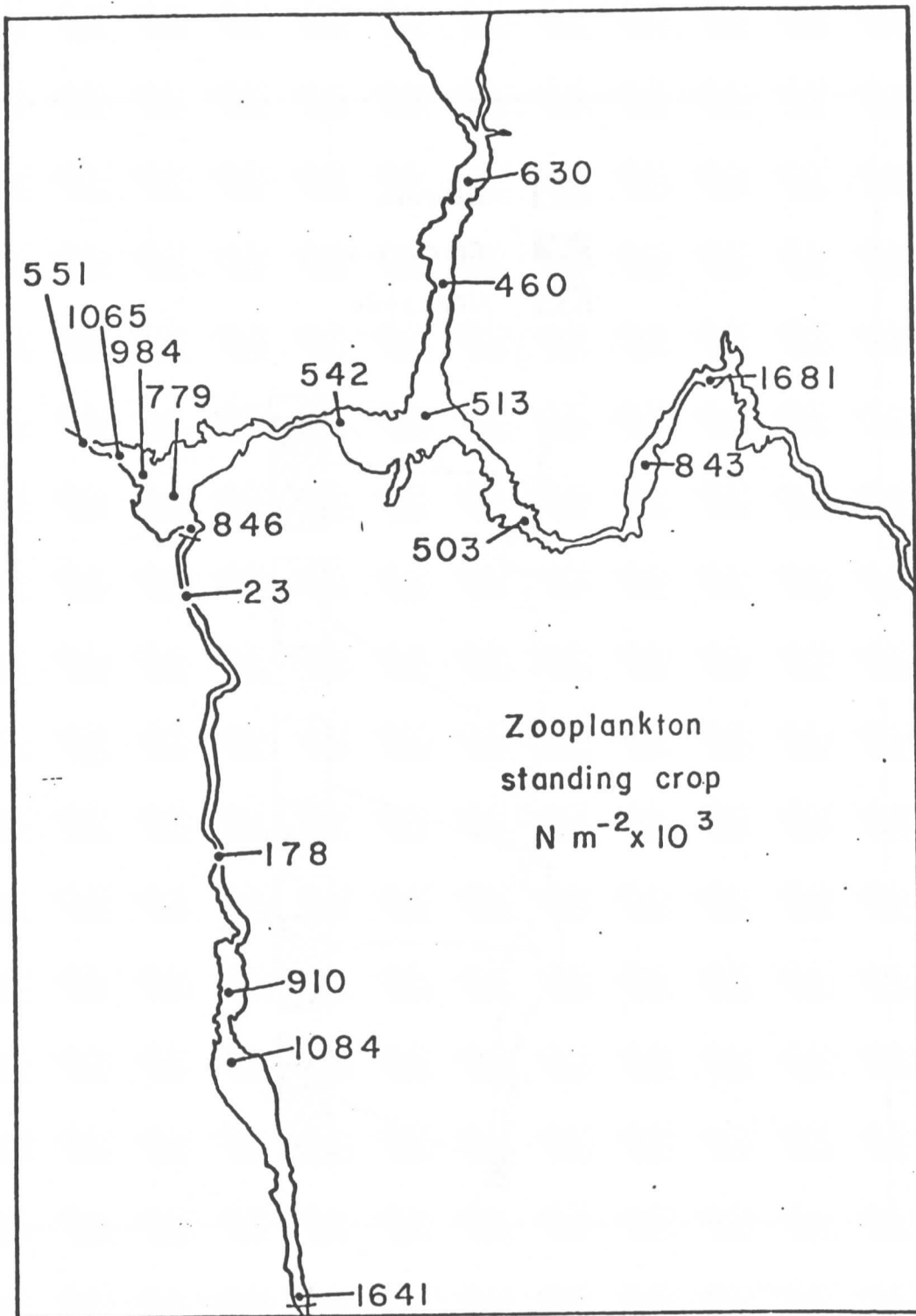
Figure 4.12.3 Zooplankton abundance in Lake
Mead and Lake Mohave.

Middle Las Vegas Bay. Zooplankton abundance was low in the river-section
of Lake Mohave but increased progressively at down-lake stations.
Generally, the abundance of zooplankton followed the same pattern as
phytoplankton productivity, indicating that food was the major factor
controlling zooplankton populations in the reservoirs.

5.0 DISCUSSION

5.1 Circulation Patterns in Lake Mead

5.1.1 Colorado River

Density currents develop in lakes and reservoirs when inflowing waters enter at a different density than receiving waters. Temperature differences are the most common cause for density currents, but dissolved and suspended solids concentration can also be important factors (Wunderlich and Elder 1973). Density varies in direct proportion to total dissolved solids (TDS) and, above 4°C, inversely with increasing temperature (Hutchinson 1957). Thus, if the inflow is warmer or lower in TDS than the reservoir, it will overflow (surface) in the reservoir. Conversely, if the inflow is colder or higher in TDS than the reservoir, it will underflow (bottom). If an underflow encounters still colder water, as frequently occurs in deep reservoirs, an interflow (midwater) develops at the depth where inflowing and receiving waters are at equal density (Wunderlich and Elder 1973). The distribution and mixing of inflow will thus vary seasonally in relation to the annual temperature cycle of inflowing and receiving waters.

The Colorado River, Virgin and Muddy Rivers and Las Vegas Wash all form density currents in Lake Mead (Anderson and Pritchard 1951, Deacon and Tew 1973, Deacon 1975,1976,1977, Baker et. al. 1977, Baker and Paulson 1978). Anderson and Pritchard (1951) conducted a detailed investigation of the density currents in 1948-1949 using temperature and salinity (TDS) relationships to trace the river-inflows. They found that

the Colorado River flowed along the bottom of the old river-channel in the winter (January-March). The underflow was detectable well into Virgin Basin and, at times, extended to Boulder Basin. The underflow created a strong convergence at the point where river-water flowed beneath lake-water. Up-lake flow of surface water occurred due to frictionally in-duced, parallel flow of lake-water (entrainment) along the boundary of the cold, river-inflow. This produced a large circulation cell in the Upper Basin as surface water was pulled up-lake to replace that entrained by the underflow.

High runoff of dilute snowmelt in the spring (April-June) reduced the salinity of the Colorado River, and this, combined with higher river temperature, caused an overflow to develop that extended down-lake into Virgin Basin and the Overton Arm. The overflow set up a circulation cell below 50 m as hypolimnion water moved up-lake to replace that entrained by the overflow.

In the summer (July-September), the inflow of the Colorado River decreased, but the salinity increased, and a deep interflow (25 m) developed in the Virgin Basin. This caused two circulation cells to develop, above and below the interflow, in the Upper Arm (Gregg and Temple Basin). These cells caused up-lake flow of surface and hypolimnion water.

The temperature of the Colorado River decreased in the fall, and this caused the inflow to sink even deeper. An interflow developed at about 50 m but then sloped toward the surface as it moved down-lake. Again, circulation cells were formed above and below the interflow producing up-lake flow of surface and bottom water.

Anderson and Pritchard's (1951) conclusions were limited primarily to the distribution of inflow in the Upper Basin. They did not report on current patterns in the Lower Basin, or exchange between basins, largely because they had no means of tracing currents beyond Boulder Canyon. The Virgin Basin acted as a large "mixing bowl" that reduced salinity gradients to the point where they could not be used to trace the inflow, or the effect of discharge from Hoover Dam on currents, in Boulder Basin. The formation of Lake Powell in 1963 buffered the low TDS inflow from snowmelt and further reduced salinity gradients in Lake Mead. However, increased discharge of saline inflow from Las Vegas Wash has provided greater salinity gradients in the Lower Basin. By relying on temperature gradients and salinity gradients created in Boulder Basin, we were able to determine the major circulation patterns in Lake Mead and trace the Las Vegas Wash density current in the Lower Basin.

The fall and winter circulation patterns induced in inflow from the Colorado River in Lake Mead have not changed appreciably since Anderson and Pritchard's (1951) study (Fig. 5.1.1). In 1977-1978, the fall circulation was characterized by a deep interflow that developed in Gregg Basin and moved down-lake to Temple Bar and Virgin Basin. Circulation cells were formed in the epilimnion and hypolimnion of the Upper Arm as lake-water was drawn up-lake to replace that diverted down-lake by entrainment along the boundaries of the interflow.

An underflow developed throughout the Upper Basin in the winter months because river-water was consideralby colder than lake-water. Since the discharge was also high, the underflow
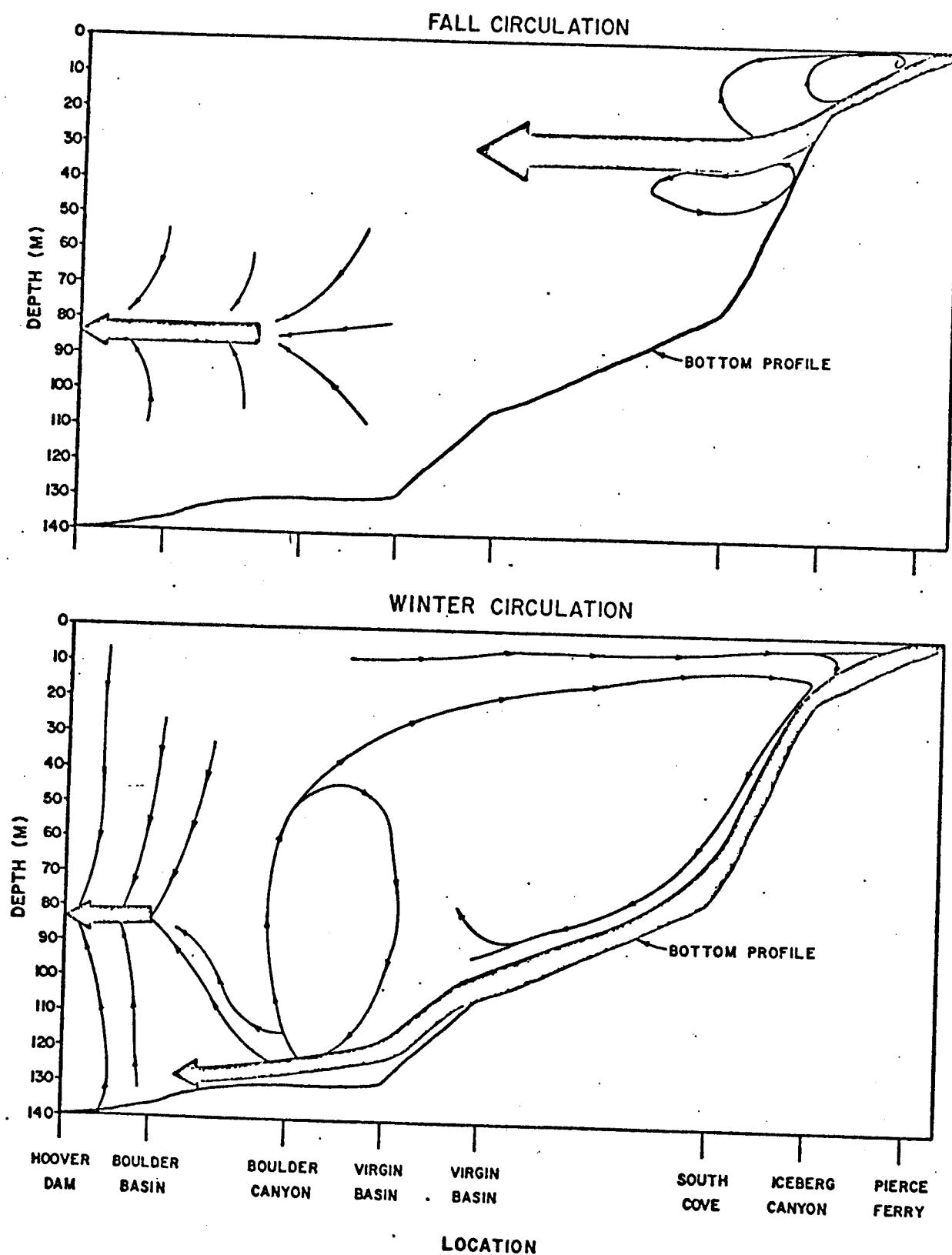
Figure 5.1.1 Fall and winter circulation patterns in Lake Mead.

caused a large circulation cell to develop in the Upper Basin.
This cell rotated clockwise from Boulder Canyon to Iceberg
Canyon. Up-lake rotation of this cell may have been further
augmented by deep upwelling at Boulder Canyon that appeared to
develop when the underflow was forced into the narrow canyon.
A smaller cell appeared to form between Virgin Basin and
Boulder Canyon where the upwelling converged with surface flow
up-lake. Rotation of this smaller cell may have been further
influenced by withdrawal current from Hoover Dam. Measurements
in February indicated that part of the Colorado River winter
inflow rose into Boulder Basin and may have been drawn to Hoover
Dam.

The river-inflow was slightly colder than lake-water in
the spring, and consequently an underflow developed in Iceberg
Canyon (Fig. 5.1.2). Mixing and entrainment of lake-water
in the canyon increased the temperature of the inflow such that
an overflow was formed in Gregg Basin (Fig 5.1.2). This moved
down-lake, above the thermocline, to Temple Basin where it
mixed with epilimnion water. The distribution of spring inflow
in 1978 differed considerably from that reported by Anderson
and Pritchard (1951) in 1948. They found that the Colorado
River formed turbid overflow that extended into Virgin Basin and
the Overton Arm during the spring. However, the spring discharge
into Lake Mead was nearly ten times greater and the temperature
was slightly warmer during that period than what it currently is
with regulated discharge from Glen Canyon Dam. Moreover, Lake
Powell now traps most of the silt derived from spring runoff,
and the turbid surface plumes reported by Anderson and Pritchard
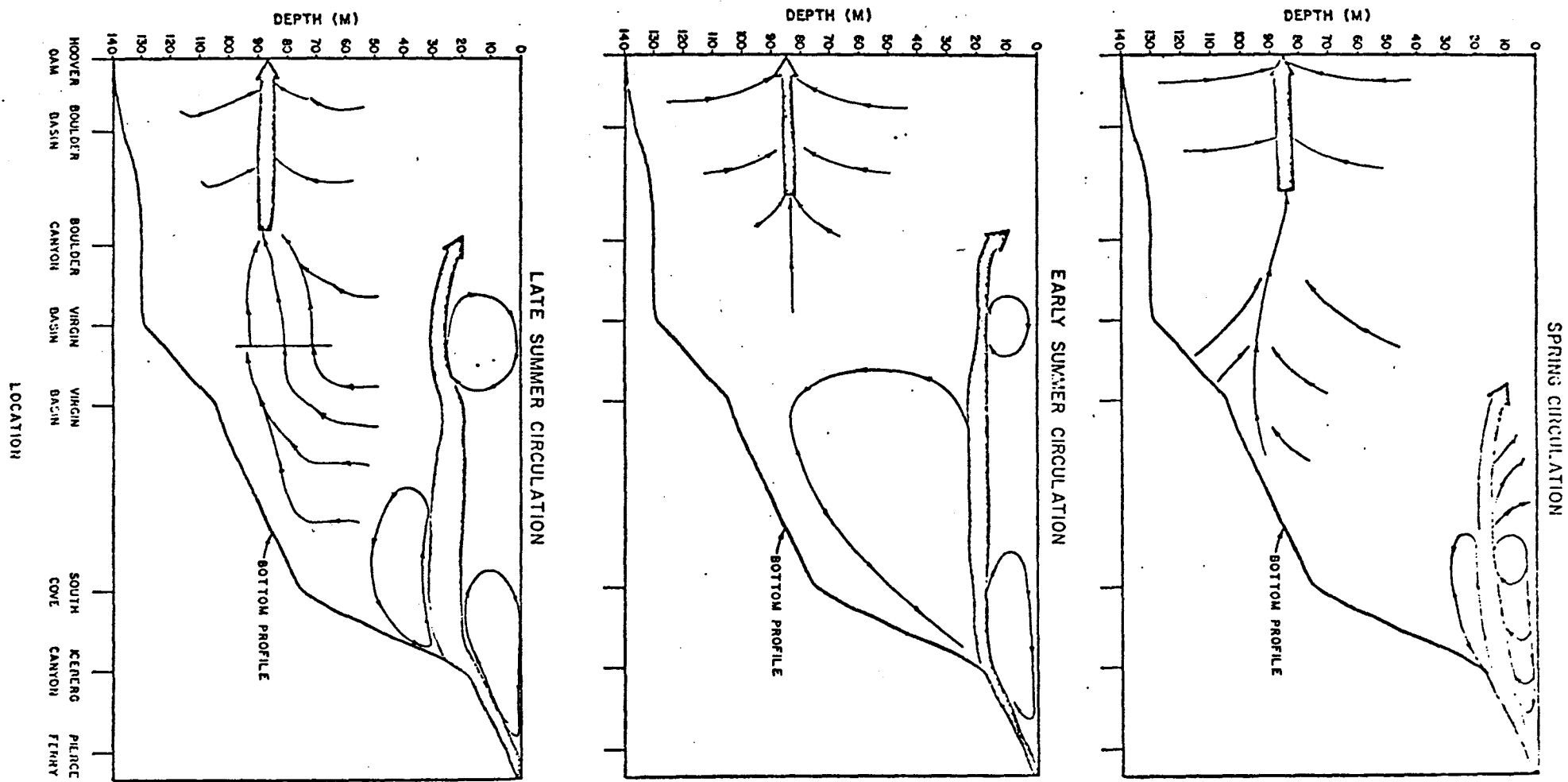
Figure 5.1.2 Spring and summer circulation patterns in Lake Mead.

(1951) are no longer evident in Lake Mead.

In early summer, the river temperature was colder than the epilimnion, and an underflow formed again at Iceberg Canyon (Fig 5.1.2). Mixing at the convergence and entrainment of lake water increased the temperature slightly, and an interflow developed at South Cove. Unlike the spring, the summer-inflow entered below the thermocline which reduced mixing of the inflow and epilimnion water in the Upper Arm. The inflow, thus, maintained a greater velocity which caused a deep circulation cell to develop in the Upper Arm when hypolimnion water was trapped and diverted down-lake by the interflow. Another circulation cell appeared to develop in the epilimnion as water was drawn up-lake to replace surface water entrained by underflow in Iceberg Canyon. As the inflow spread into Virgin Basin and the Overton Arm, the velocity apparently decreased allowing for more mixing with the epilimnion. However, it was not entirely mixed in Virgin Basin since part of the inflow reached Boulder Canyon and may have entered Boulder Basin during the early summer.

The temperature of the Colorado River further decreased with increasing discharge from Lake Powell in late summer (Fig. 5.1.2). This produced an underflow at Iceberg Canyon, but a broad interflow developed again at South Cove. The increased flow caused greater mixing of the inflow, and the entrainment zone was broader than in early summer. The velocity of inflow appeared to decrease with greater mixing, and only a small circulation cell was formed in the epilimnion between South Cove and Iceberg Canyon. The current velocity further

decreased in down-lake areas as the inflow spread in Virgin Basin, Echo Bay and Boulder Canyon, resulting in a slight decrease in temperature and more vertical mixing in these areas.

The water temperature in the epilimnion of the Virgin Basin and Overton Arm was usually slightly lower than the Lower Basin in early summer. From July to August, the epilimnion temperature at the main reservoir stations decreased by approximately 3°C, followed by a 2°C drop from August to September. Over this period, the thermocline dropped by nearly 10 m. This was unexpected since the air temperature and solar radiation remained high in August and September. However, it appears that this late summer decrease in temperature, and temperature differences between each basin, may have been caused by inflow and mixing of cold river-water during late summer.

The formation of Lake Powell in 1963 altered the natural temperature and discharge cycles of the Colorado River (Fig. 5.1.3). From May through September, the river temperature currently ranges from 10-20°C colder than Lake Mead, compared to 2-5°C colder prior to formation of Lake Powell. Moreover, the discharge is considerably higher in late summer than for comparable periods prior to 1963. The cumulative inflow volume of the Colorado River during the summer of 1978 was $5.3 \times 10^9 m^3$ which is equivalent to the amount of water stored from 1-15 m in Lake Mead, at the current lake elevation. It appears that prolonged discharge of cold, river-inflow and mixing in Lake Mead caused a reduction in temperature and premature erosion of the thermocline in parts of the Upper Basin by mid-summer, and at all the main basin stations by late summer. Annual and
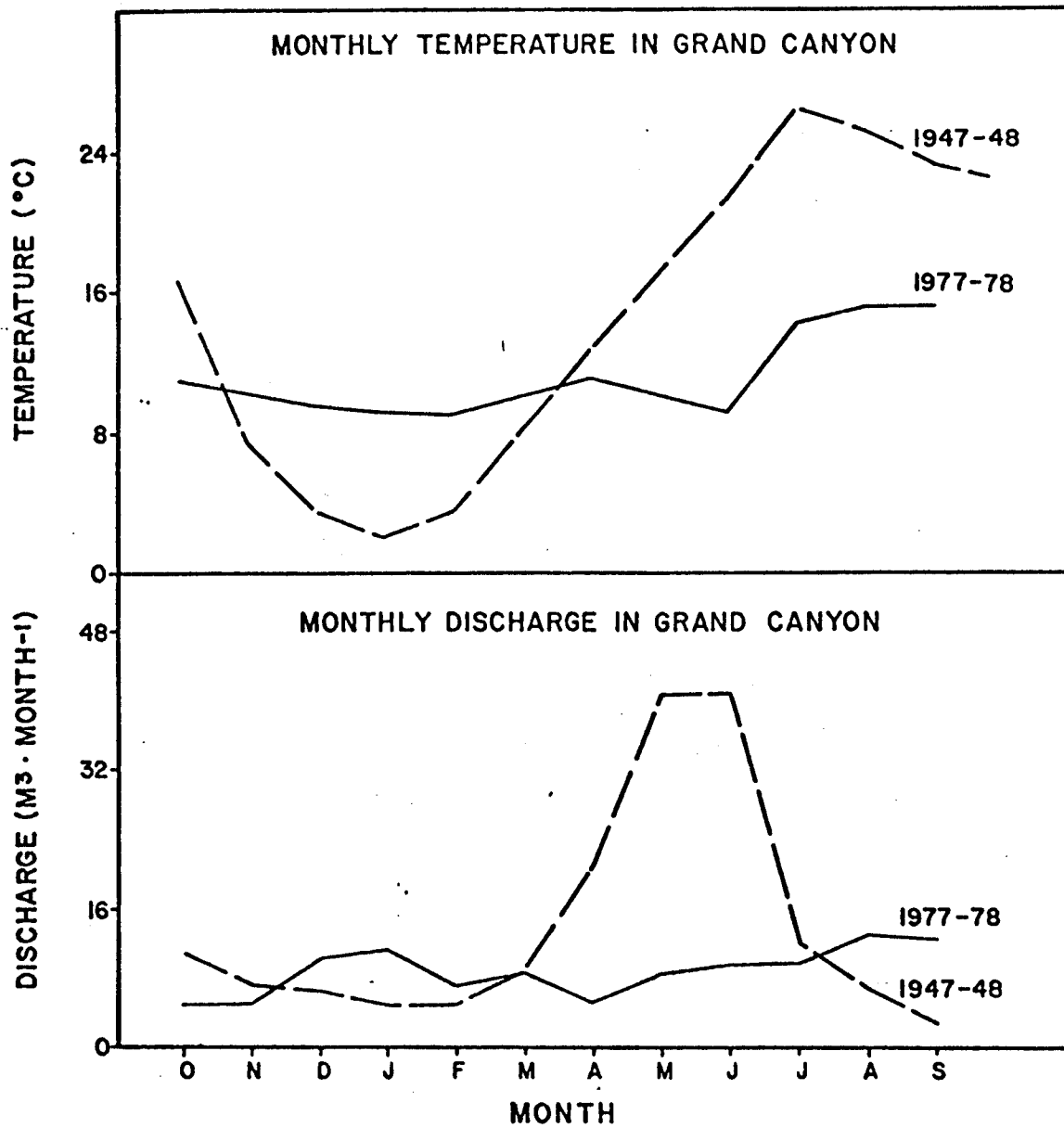
Figure 5.1.3 Temperature and discharge cycles
of the Colorado River in 1947-48
and 1977-78.

seasonal variations in the rate of discharge from Lake Powell
could thus be expected to cause considerable variation in the
temperature structure and mixing processes in Lake Mead.

5.1.2 Origin of Replacement Water for Discharge from Hoover Dam

Discharge of water from a reservoir produces a horizontal,
cone-like withdrawal layer near the penstocks (Wunderlich and
Elder 1973). The width of the withdrawal layer varies with the
rate of discharge and the distance it extends up-lake varies with
the duration of the discharge cycle. The withdrawal layer is
further influenced by vertical and seasonal changes in tem-
perature which alter the density and, hence, buoyancy of replace-
ment water. Warm water is less dense and thus more buoyant
than cold water. This counteracts the opposing gravitational
forces generated by discharge from the penstocks. Depending
on the temperature of the reservoir versus the rate and duration
of discharge, replacement water can originate either from over-
lying water near the penstocks or from cold-water reserves up-
lake from the dam.

In the winter and early spring, when Lake Mead was iso-
thermal, the density gradient was not sufficient to counteract
gravitational forces generated at the discharge. Consequently,
replacement water was drawn from the entire water column near
the dam (Fig. 5.1.2). After thermal stratification developed,
replacement water was initially drawn from cold water (12.0-
12.5°C) in the hypolimnion of Boulder Basin. This, in turn,
caused hypolimnion water (11.5°-12.0°) to shift down-lake from
Virgin Basin. When that was also discharged, replacement water
was eventually derived from slightly warmer, overlying (11.5-

13.0°C) water in the upper hypolimnion. This sequence was evident by changes in the deep-water isotherms over the summer.

The 13.0°C isotherm descended from an average depth of 40 m in April to 70 m by September. This first occurred in the area near Hoover Dam in early summer followed by a similar pattern in Boulder Basin by mid-summer, and in Virgin Basin by late summer. When the cumulative discharge is sufficient to exhaust the coldest water initially present in that area of the reservoir, slightly warmer water descends from the upper-hypolimnion to replace it. This created a great deal of temperature instability in the hypolimnion of Lake Mead.

5.1.3 Las Vegas Wash Density Current

It has been known for several years that the saline inflow from Las Vagas Wash forms a density current in Las Vegas Bay (Hoffman et al. 1967, Hoffman et al. 1971, Deacon and Tew 1973, Deacon 1975,1976,1977, Baker et al. 1977, Baker and Paulson 1978). Since the Las Vegas Wash inflow is also enriched with nutrients from sewage and groundwater, the distribution and mixing of the density current have a direct influence on phytoplankton growth in Las Vegas Bay. The distribution of the density current appears to be governed primarily by temperature and salinity differences between the inflow and the bay, and by the morphometry of Las Vegas Bay.

The temperature of the Las Vegas Wash inflow was usually lower and the salinity was greater than surf e waters of Las Vegas Bay. Consequently, the density current flowed primarily along the bottom of the inner bay during the year (Figs. 5.1.4-5.1.5). For a brief period in the spring, the temperature of

LAS VEGAS BAY
FALL CIRCULATION

DEPTH (M)

BOTTOM PROFILE

LAS VEGAS BAY
WINTER CIRCULATION

DEPTH (M)

BOTTOM PROFILE

HOOVER DAM | BOULDER BASIN | OUTER LAS VEGAS BAY | MIDDLE LAS VEGAS BAY | INNER LAS VEGAS BAY | NORTH SHORE ROAD

LOCATION
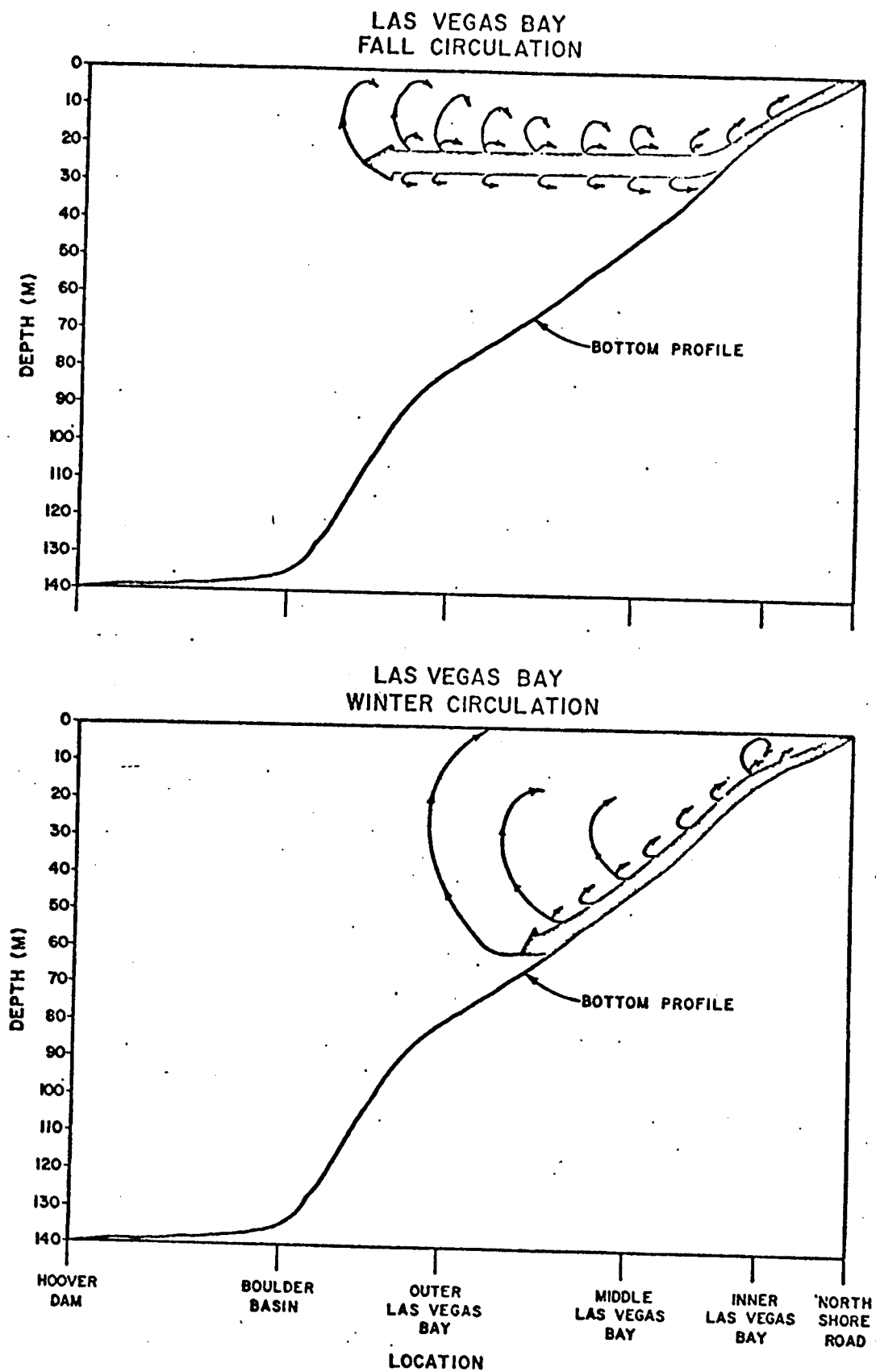
Figure 5.1.4 Fall and winter circulation
patterns in Las Vegas Bay,
Lake Mead.

allows for greater horizontal spreading of the saline inflow.
The density current is therefore subject to a decrease in
velocity and greater contact with overlying water which results
in complete mixing of the inflow between the middle and outer
bay.

In the spring, when the wash temperature exceeded that
in the bay, the density of the inflow was not sufficient to
resist vertical mixing, and the density current was dispersed
throughout the hypolimnion of the middle bay. With formation
of thermal stratification in early-summer (May-June), a broad
interflow developed at the point where the density current
intersected the thermocline. This formed at a depth of 10-15m
between the inner and middle bay. The interflow did not extend
much beyond the middle bay because of more horizontal spreading
along the thermocline in that area. This dispersed the density
current over a greater area which enhanced mixing with the
epilimnion. Although this appeared to be the predominant
distribution pattern in the summer, the density current changed
somewhat when the temperature of the epilimnion decreased in
the Outer Las Vegas Bay and Boulder Basin. The density current
still flowed along the thermocline in the middle bay where
the temperature of the epilimnion was near 27°C in August.
However, when the density current encountered the slightly
cooler water beyond the middle bay, it ascended above the
thermocline and was mixed with the epilimnion. Mixing of the
saline, phosphorus-rich inflow increased the conductivity of
the epilimnion to 1200 μmhos. cm^{-1} and the phosphorus con-
centration to 5-10 $\mu g \cdot l^{-1}$. This, in turn, is what produced

the late-summer increase in productivity in the outer bay and Boulder Basin.

5.2 Circulation Patterns in Lake Mohave

The seasonal circulation patterns in Lake Mohave were governed primarily by the discharge of cold (12.0-12.5°C) water from Hoover Dam. Except for the winter period, when the river and lake were at equal temperatures, the Colorado River formed an underflow in Lake Mohave. The circulation pattern that this produces is illustrated in Fig. 5.2.1 for high and low discharge from Hoover Dam in the summer.

A cold-water wedge was formed in up-lake areas under high discharge from Hoover Dam. The thermocline was elevated by several meters as the cold river-water was forced under the warmer lake-water. Entrainment of surface water by the underflow and down-lake flow of the hypolimnion water mass caused a reverse circulation cell to develop in Cottonwood Basin, as surface water is drawn up-lake to replace that pulled down by the underflow. Upwelling occurred periodically at Davis Dam when the discharge there was not sufficient to accommodate the flow of river-water moving in the hypolimnion.

Under low discharge from Hoover Dam the cold-water wedge receded in up-lake areas, and the thermocline returned to a normal position. This, however, appeared to cause a seiche which, in turn, produced up-lake flow of epilimnion water in Eldorado Canyon and Little Basin. The fluctuating high and low discharge of cold-water from Hoover Dam thus created a great deal of instability in the temperature structure and circulation in the upper end of Lake Mohave. This was also

SUMMER CIRCULATION PATTERNS IN LAKE MOHAVE AT HIGH AND LOW DISCHARGE
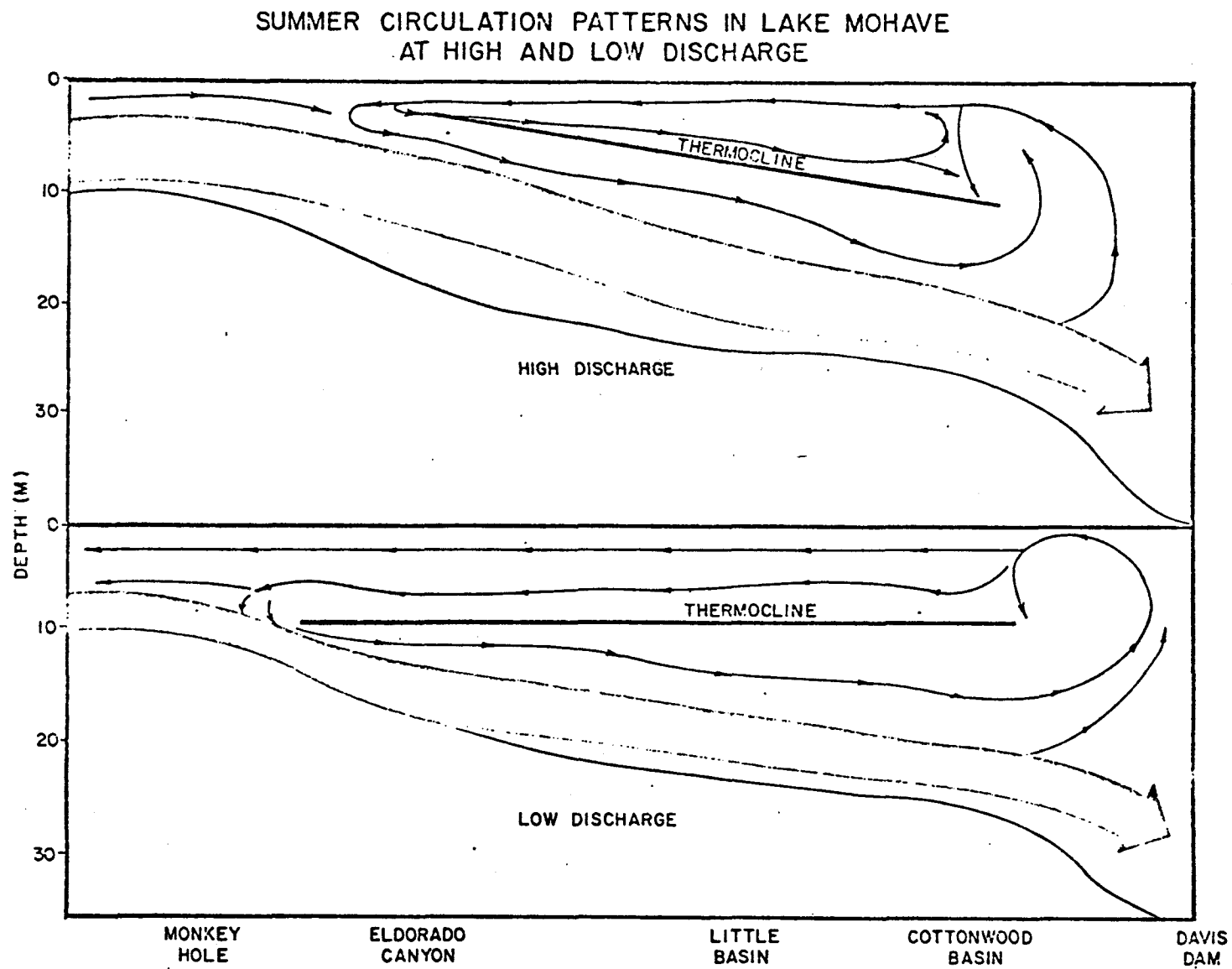
Figure 5.2.1   Summer circulation patterns for high and low
discharge in Lake Mohave.

evident in the location of the interface between river-water and lake-water.   The interface was highly visible because mixing of warm lake-water with cold, nutrient-rich river-water produced a marked increase in phytoplankton productivity in this area.   We observed the interface as far down-lake as river mile 24 (below Hoover Dam) and as far upstream as river mile 14.   The relationship between discharge from Hoover Dam and location of the interface is discussed further in Section 5.5.2.

5.3 Nutrient Budget and Dynamics

5.3.1 Lake Mead

The major circulation patterns and distribution of river inflows in Lake Mead had a significant influence on the nutrient budget and dynamics in each basin of the reservoir. Direct measurement of nutrient utilization and recycling was beyond the scope of our study.   However, we did construct nutrient budgets for the Upper and Lower Basin of Lake Mead which reflect the collective influence of these processes on the nutrient status of the reservoir.

The inorganic nutrient budgets were markedly different in the Upper and Lower Basin.   Proportional amounts of inorganic nitrogen and phosphorus (42%) were retained in the Upper Basin, but nitrogen retention decreased to 7.4% and phosphorus dropped to 33% in the Lower Basin.

There are some unique problems associated with estimating nutrient loads in Boulder Canyon that could, in part, account for some of the differences in nutrient retention in each basin.   We estimated flow in Boulder Canyon by simply assuming

that water discharged from Hoover Dam in each month would be replaced by a corresponding inflow from the Upper Basin. However, in June we observed reverse surface currents in the canyon, and, therefore, the flow of the entire water column is not always unidirectional (Virgin Basin→Boulder Basin). This poses a problem in estimating nutrient loads at Boulder Canyon because in the Lower Basin the phosphorus concentration was higher throughout the year, and nitrate was lower in the summer than in the Upper Basin. Thus, if water periodically moved up-lake from Boulder Basin to Boulder Canyon, our estimates of phosphorus retention were too low in the Upper Basin and too high in the Lower Basin, and vice versa for nitrogen retention. It is not known to what extent water exchange between the basins contributed to the difference in nitrogen and phosphorus retention computed for the Upper and Lower Basins.

In order to more precisely estimate nutrient budgets for the respective basins, current velocity and direction would have to be measured in conjunction with nutrient concentration, so that flow-proportional nutrient loads could be computed at Boulder Canyon. However, despite some uncertainty introduced by these problems, the nutrient budgets still appear to reflect basic differences in the nutrient status of each basin. The proportional retention of inorganic nitrogen and phosphorus, as in the Upper Basin, indicates that these nutrients were being retained in a common nutrient pool. Assimilation of inorganic nitrogen and phosphorus by phytoplankton in the euphotic zone and subsequent deposition of moribund phytoplankton cells, containing nitrogen and phosphorus, in the sediments

probably accounts for the proportional retention of nutrients in the Upper Basin (Paulson and Baker 1979a). Although the same process also occurs in the Lower Basin, there appear to be other mechanisms operating there that act to selectively retain phosphorus, but accelerate loss of nitrogen from the reservoir and, thus, account for the disproportional retention of these nutrients.

There are several chemical processes operating in lakes and reservoirs whereby phosphorus can be selectively retained in lake sediments (Syers et al. 1973). Inorganic phosphorus can form insoluble precipitates with calcium carbonate (hydroxyapatite) and iron (ferric phosphate), and it can adsorb to various oxides as well as clay and silt particles (Syers et al. 1973). Chemical conditions in Las Vegas Wash and the Inner Las Vegas Bay are such that it is likely that one, or all, of these processes acts to retain a greater proportion of the inflowing phosphorus than that actually lost by sedimentation of phytoplankton cells.

Calcium carbonate is near saturation in Las Vegas Wash, and the pH in the Inner Las Vegas Bay frequently exceeds 9.0 during periods of high phytoplankton productivity. It is, therefore, likely that precipitation of calcium carbonate, and formation of hydroxyapatite, occurs in the Inner Las Vegas Bay. The concentration of soluble iron is also very high in Las Vegas Wash (USGS 1977) and in the range of that reported by Viner (1975) suitable for the formation of insoluble iron-phosphorus precipitates. Chemical analyses of sediment in Las Vegas Bay (Goldman 1976) indicate that the sediments

contain a fairly high concentration of phosphorus in assoc-
iation with carbonate and iron (EDTA, extractable P). This,
in part, could account for the greater retention of phosphorus,
relative to nitrogen, in the Lower Basin. However, even with
these additional storage mechanisms, phosphorus retention in
the Lower Basin was low (33%) by comparison to the Upper Basin
(42%).

The inorganic phosphorus load discharged at Hoover Dam
was roughly twice as great as the input from the Colorado
River at Pierce Ferry and four times greater than the input to
Boulder Basin from Boulder Canyon. This increase was caused
primarily by the large input of phosphorus from Las Vegas Wash
and the inefficient utilization of phosphorus in the Boulder
Basin. For a large part of the year, phosphorus input from
Las Vegas Wash flowed into the hypolimnion of Las Vegas Bay
and Boulder Basin. This, plus release of phosphorus from de-
caying phytoplankton cells or, possibly, from the sediments
themselves, increased the concentration of phosphorus in the
hypolimnion of the Boulder Basin up to 15 $\mu g \cdot 1^{-1}$ during the
spring and summer. Water discharged from Hoover Dam during
the summer was initially drawn from the hypolimnion of the
Lower Basin. Phosphorus retention was, therefore, greatly
reduced because a large portion of the hypolimnion, containing
relatively high concentrations of phosphorus, was discharged
from Hoover Dam (Paulson and Baker 1979a).

The inorganic nitrogen load discharge at Hoover Dam was
1.2 times greater than the input from Boulder Canyon, and re-
tention was reduced to 7.4% in the Lower Basin. Again, this

appears to be related to hypolimnion discharge at Hoover Dam (Paulson and Baker 1979a, 1979b). Replacement water for that discharged from the Lower Basin in the summer was drawn from the hypolimnion of Virgin Basin. There was no appreciable difference in the inorganic nitrogen concentration in the hypolimnion of the two basins. Therefore, the nitrogen input via replacement water from the hypolimnion of Virgin Basin was nearly equal to output from Hoover Dam. Moreover, this input occurred below the euphotic zone, and the principal mechanism of nitrogen retention (uptake by phytoplankton and subsequent deposition in the sediment) was bypassed which significantly reduced the rate of nitrogen retention in the Lower Basin.

The inorganic nitrogen that was retained in the Lower Basin was derived primarily from: (i) that contained in the euphotic zone after winter mixing, (ii) inflow from Las Vegas Wash and (iii) inflow from the epilimnion of Virgin Basin. However, with the high phosphorus loading from Las Vegas Wash these nitrogen inputs were not sufficient to sustain the uptake by phytoplankton in the Lower Basin and inorganic nitrogen became depleted in the euphotic zone by June and remained low to September. By comparison, phosphorus deficiency and a continuous input of organic nitrogen into the epilimnion and metalimnion from the Colorado River prevented phytoplankton from totally depleting inorganic nitrogen in the euphotic zone of the Upper Basin. However, the concentration of inorganic nitrogen at Virgin Basin, Echo Bay and Overton was reduced by one-third the winter concentration, despite the low input

of phosphorus from the Colorado River. This indicates that
phosphorus was used very efficiently by phytoplankton in the
Upper Basin. Rapid recycling of phosphorus is fairly charac-
teristic of lakes (Rigler 1964), and, thus, relatively high
rates of phytoplankton productivity can be maintained on low
ambient phosphorus concentrations.

The deficiency of inorganic nitrogen that developed in
the Lower Basin was favorable for the growth of bluegreen
algae in late summer. Fairly large numbers of Anabaenopsis
raciborskii, with heterocysts, were found in phytoplankton
samples collected from Las Vegas Bay and Boulder Basin in
August and September. Although direct measurements of ni-
trogen fixation were not made, the occurrence of heterocysts
on bluegreen algae indicates that they are capable of fixing
atmospheric nitrogen (Fogg et al. 1973). This represents an
additional input of nitrogen that could result in higher
nitrogen retention in the Lower Basin than that actually
computed from the nutrient budgets. However, nitrogen fixation
is probably small relative to nitrogen input from Las Vegas
Wash and the Colorado River because the nitrogen fixing bluegreen
algae were only present for a short period in the late summer.

The relative availability of nitrogen and phosphorus
from the principal inflows and the relationship of these to
the phytoplankton growth during the summer appear to be the
principal factors governing nutrient retention in each basin
of Lake Mead. Although we are currently not able to quantify
the relationships, we feel the following summary is an accurate
description of how these factors interact to influence the

the nutrient retention in each basin.

The Colorado River provides a high nitrogen and low, but fairly constant, phosphorus source to the metalimnion and epilimnion of the Upper Basin in the summer. Mixing of this inflow distributes nutrients to the euphotic zone of the Upper Basin where they are assimilated by phytoplankton. However, a deficiency of phosphorus, or possibly iron, prevents the phytoplankton from utilizing all the inorganic nitrogen in the Upper Basin. The unused nitrogen in the epilimnion of the Upper Basin and inflow from Las Vegas Wash become the principal nitrogen inputs to the euphotic zone of the Lower Basin. However, with high phosphorus loading from Las Vegas Wash, the inorganic nitrogen becomes depleted by phytoplankton in the Lower Basin by June and remains low through September. Water drawn from the hypolimnion of Virgin Basin for replacement of that discharged from Hoover Dam is the largest input of inorganic nitrogen to the Lower Basin in the summer. However, this is largely unavailable to phytoplankton because thermal stratification prevents mixing into the euphotic zone. This effectively bypasses the principal mechanism (uptake by algae) of nutrient retention in the reservoir and, consequently, overall nitrogen retention is greatly reduced in the Lower Basin.

Periodic phosphorus loading of the hypolimnion from Las Vegas Wash, combined with hypolimnetic discharge from Hoover Dam also reduces phosphorus retention in the Lower Basin. This, however, may be balanced somewhat by greater phosphorus retention in the Lower Basin due to formation of insoluble

carbonate and iron precipitates and scavenging of inorganic phosphorus in the Inner Las Vegas Bay. Development of a nitrogen deficiency in the Lower Basin during early summer reduces phosphorus utilization by the phytoplankton, and the concentration of phosphorus increases accordingly. This creates an environment suitable for growth of nitrogen fixing bluegreen algae which provide an additional input of nitrogen to the Lower Basin in mid-summer.

A decrease in surface temperature in the late summer and increased vertical mixing bring nutrients, primarily nitrate, back into the euphotic zone which, in combination with the phosphorus that is already present, trigger a late summer pulse of phytoplankton productivity in the Lower Basin. With further decreases in temperature in the fall and winter, the reservoir mixes completely and the concentration of inorganic nitrogen is essentially uniform vertically and horizontally throughout the reservoir. This reduces the inorganic nitrogen gradient between the Colorado River and the Upper Basin and between the Upper and Lower Basin. Thus, inorganic nitrogen input from the Colorado River nearly equals output at Boulder Canyon which is nearly equal to output at Hoover Dam during the winter. However, mixing of phosphorus-ladened inflow from Las Vegas Wash in the Lower Basin increases the phosphorus concentration threefold over that in the Upper Basin. This causes a large increase in the phosphorus output from Hoover Dam relative to the input derived from Boulder Canyon and the Colorado River.

5.3.2 Lake Mohave

The principal nutrient source for Lake Mohave is derived from the hypolimnion of Lake Mead via discharge from Hoover Dam. This water is enriched with nitrogen and phosphorus from decomposition of moribund phytoplankton cells sinking from surface waters and direct loading of the hypolimnion from the Las Vegas Wash and Colorado River inflows. Lake Mohave retained 37% of the dissolved phosphorus input and 31% of the inorganic nitrogen input derived from Hoover Dam. This is a relatively high rate of nutrient retention, considering that the hydraulic retention time of Lake Mohave is only 80 days. However, the shallow depth, greater surface to volume ratio and more turbulent current patterns in Lake Mohave all promote greater mixing and nutrient availability to phytoplankton in the euphotic zone. The average productivity in Lake Mohave was typically higher than that in Lake Mead, reflecting the greater nutrient availability. The point where river-water converged with lake-water in the upper end of Lake Mohave was extremely productive and often exceeded the productivity in Las Vegas Bay.

In addition to greater nutrient availability, the nutrient input to Lake Mohave was supplied at a more optimum inorganic nitrogen: phosphorus ratio for phytoplankton growth than in Lake Mead. The Colorado River entered Lake Mead at an N:P ratio of 85:1, and was severely phosphorus deficient. Conversely, the Las Vegas Wash inflow had an N:P ratio of 4:1 and phosphorus was supplied in excess relative to nitrogen. The Upper Basin of Lake Mead was phosphorus-limited and the Lower

Basin nitrogen-limited during most of the summer. This reduced

overall nutrient retention in the reservoir because one nutrient

was present in short supply relative to the other in each

basin. The N:P ratio of water discharged from Lake Mead into

Lake Mohave was 28:1. In the summer, surface waters at the

main reservoir stations in Lake Mohave had N:P ratios of about

10:1 which is close to the optimum required by phytoplankton.

Thus, both nitrogen and phosphorus were utilized more effi-

ciently in Lake Mohave which tends to increase nutrient re-

tention in the reservoir.

The true nutrient retention in Lake Mohave, however,

appears to be considerably less than what we estimated by

difference between the input from Hoover Dam and output at

Davis Dam of inorganic nutrients. Priscu (1978) constructed

a budget for total nitrogen and total phosphorus and found that

only 4% and 3%, respectively, of the nutrients were actually

stored in the reservoir. This indicates that the inorganic

nutrients derived from discharge at Hoover Dam were simply

converted to organic form and flushed from the reservoir,

rather than being deposited in the sediments. This, however,

could be expected due to the strong underflow of river-water

which greatly increases the flushing rate in Lake Mohave.

Organic material settling from surface waters would encounter

the underflow and be transported down-lake and discharged at

the dam.

5.4 Trophic Status and Relationship to Nutrient Loading

5.4.1 Lake Mead

Numerous criteria have been developed for assessing

the trophic status of lakes and reservoirs. Those most commonly used are rates of phytoplankton productivity and chlorophyll-a concentration. Likens (1975) has summarized the ranges over which these criteria are used to characterize lakes according to trophic state (Table 5.4.1).

In terms of annual average chlorophyll-a concentration, the Upper Basin of Lake Mead was oligotrophic, Boulder Basin and Hoover Dam were oligotrophic-mesotrophic and Las Vegas Bay was mesotrophic. Except for March at Iceberg Canyon, chlorophyll-a never exceeded 3 $\mu g \cdot 1^{-1}$ in the Upper Basin and was usually in the low range of values given for oligotrophic lakes.

The trophic state in the Upper Basin was oligotrophic-mesotrophic, and the Lower Basin was mesotrophic-eutrophic on the basis of average daily phytoplankton productivity. In the Upper Basin, daily phytoplankton productivity ranged from oligotrophic at some stations during the winter to eutrophic at Iceberg Canyon in March. The Inner and Middle Las Vegas Bay were eutrophic for most of the year, but, elsewhere in the Lower Basin, daily productivity only reached a eutrophic level in August and September.

Lake Mead would be classified as an oligotrophic-mesotrophic reservoir on the basis of average daily phytoplankton productivity and chlorophyll-a across the whole reservoir. This trophic state is considerably lower than that predicted for Lake Mead on the basis of total phosphorus loading (EPA 1978a). Lake Mead should be eutrophic at the current rate of total phosphorus loading, but clearly, this is not the case.

Table 5.4.1 Various criteria for assessing the trophic
status of lakes and reservoirs (from Likens
1975).

| Trophic Status | Parameter | |
	Phytoplankton Productivity (mg $C \cdot m^{-2} \cdot day^{-1}$)	Chlorophyll-a ($\mu g \cdot \ell^{-1}$)
Oligotrophic	50 - 300	.3 - 3.0
Mesotrophic	250 - 1000	2.0 - 15.0
Eutrophic	600 - 8000	10 - 500

The discrepancy between the actual and predicted trophic state of Lake Mead is due to several factors related to nutrient distribution and limitation.

Total phosphorus loading models (e.g. Vollenweider 1968) may not be well suited for reservoirs that receive large inputs of silt because a considerable portion of the phosphorus is usually bound to silt and clay particles and, thus, is not directly available to phytoplankton (Bachman and Canfield 1979). However, others assume that at some point, the phosphorus will become available to phytoplankton, regardless of the form in which it enters the reservoir. This may be so where the silt remains suspended in the water for long periods, and the phosphorus is released by chemical or microbial processes. Such is the case in Lake Powell, where the Colorado River forms a turbid overflow in the spring and contributes substantial amounts of phosphorus to surface layers of the reservoir (Gloss et al. 1979). This was probably also the case in Lake Mead prior to the formation of Lake Powell. Anderson and Pritchard (1951) found that silt-ladened riverwater was transported down-lake along the surface to Virgin Basin and Overton Arm during the spring. This no longer occurs in Lake Mead due to drastic reduction of the silt load after Lake Powell was formed.

Phosphorus loading to the Upper Basin has probably also been reduced which contributes to phosphorus-limited conditions of this basin. The silt that does enter the reservoir is deposited rapidly near the mouth of the river. It seems that as layer after layer of silt accumulates in the bottom,

phosphorus contained in the layers below will be permanently trapped in the sediment. EPA (1978a) estimated that Lake Mead retained 93% of the total phosphorus input versus 52% for total nitrogen. The most likely site for additional phosphorus retention is in the sediment via deposition of silt (EPA 1978a). Thus, the sediments are probably a permanent sink, rather than a source, of phosphorus for phytoplankton in Lake Mead.

Inorganic phosphorus is, perhaps, a better measure of that directly available to phytoplankton. Of this, only about half of the inflow from the Colorado River and one third of that from Las Vegas Wash was retained in each basin of Lake Mead. The low retention of phosphorus was, in part, due to periodic underflow of the the Las Vegas Wash inflow which reduced phosphorus availability to phytoplankton. In addition, phytoplankton can only use phosphorus or nitrogen to the extent that each is supplied in proportion to their requirements (e.g. 8N:1P). However, in the Upper Basin, phosphorus is deficient due to the low input from the Colorado River. In the Lower Basin, nitrogen is deficient in the summer since phosphorus is present in excess and most of the nitrogen input from the Upper Basin is drawn through Boulder Canyon below the euphotic zone. The disproportional supply of nitrogen and phosphorus to each basin tends to lower the trophic state of the reservoir. If the high nitrate input from the Colorado River flowed directly into the Lower Basin, where phosphorus is present in excess, the productivity in that basin would be considerably higher. Greater input of phosphorus to the Upper Basin would produce similar results in that basin.

There is one other factor operating in Lake Mead that acts

to reduce nutrient retention and, hence, lower the trophic state of the reservoir. The discharge from Hoover Dam is high (ca. 350 $m^3 \cdot sec^{-1}$), and this water is drawn from the hypolimnion (83 m). There is a significant vertical gradient of inorganic nitrogen and phosphorus concentration in the Lower Basin. The highest concentration of nutrients in the water column occurs in the hypolimnion due to periodic underflow of the inflow from Las Vegas Wash and the Upper Basin and nutrient release from decomposing phytoplankton settling to the bottom. This, combined with high discharge from the hypolimnion, effectively strips nutrients from Lake Mead. If Hoover Dam was operated with an epilimnion rather than hypolimnion discharge, the nutrient status of Lake Mead would be quite different.

This is evident in the comparison of nitrate and phosphorus loss from Lake Mead in 1978 (January-September) under the current hypolimnion discharge and simulated epilimnion discharge (Fig. 5.4.1). The epilimnion discharge was simulated by multiplying the monthly discharge from Hoover Dam by the concentration of nitrate and phosphorus in the epilimnion (10 m) at the Hoover Dam station in Lake Mead. Annual nitrate loss from the hypolimnion discharge would exceed that from an epilimnion discharge by 75%. The greatest difference would occur in the summer months when nitrate is reduced in the epilimnion by phytoplankton uptake. Phosphorus loss would be 46% greater for the hypolimnion than epilimnion discharge. However, here the loss rate would be greatest in the spring and early summer. This is largely due to phosphorus loading
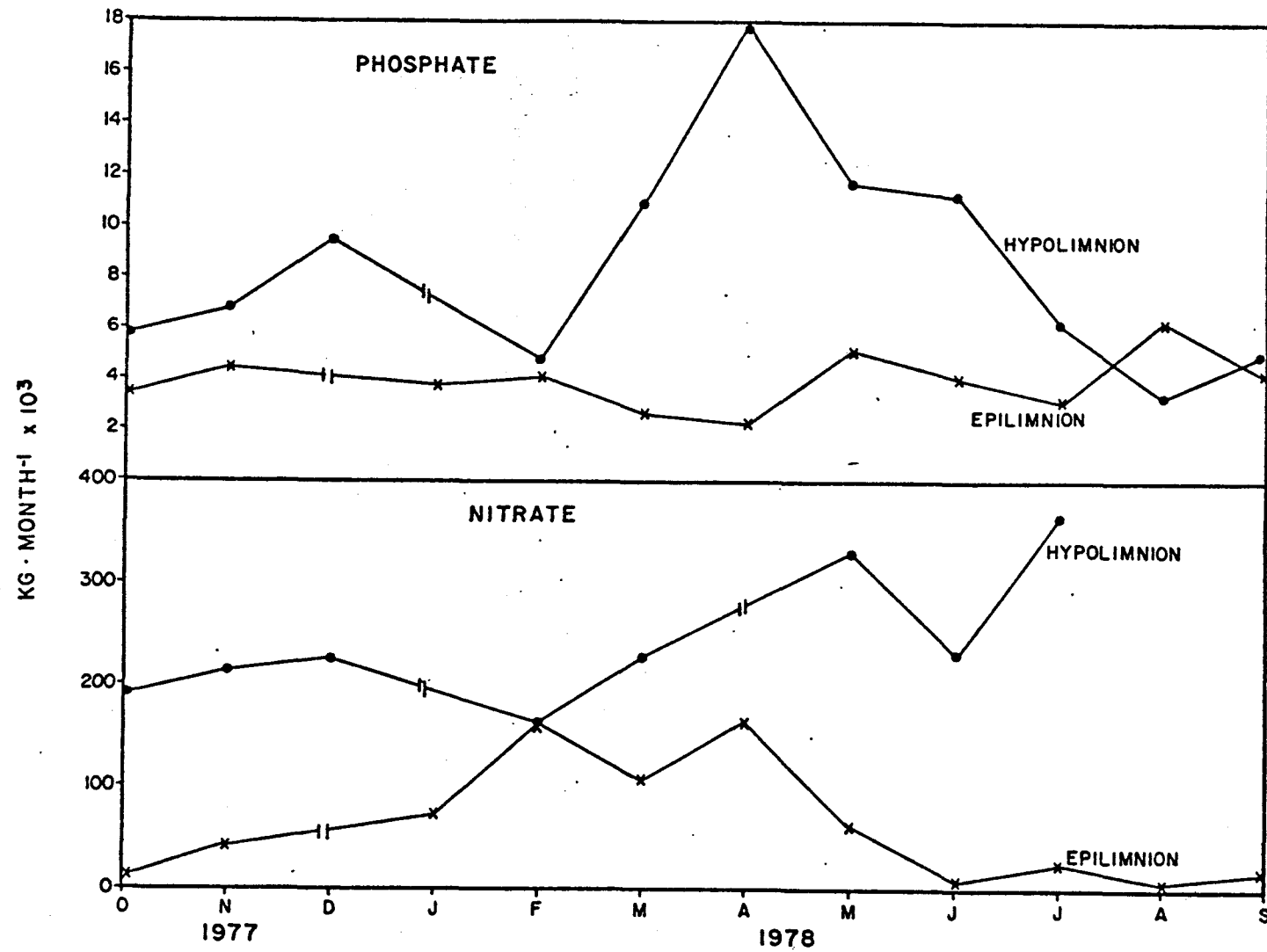
Figure 5.4.1   Nutrient loss from Hoover Dam for epilimnion
and hypolimnion discharge.

of the hypolimnion by underflow of the Las Vegas Wash inflow which increases the phosphorus concentration of deep water during those periods.

Thus, in a relatively short time period there is a considerable increase in the loss of nitrate and phosphorus with hypolimnion discharge. Moreover, since the relative loss of each nutrient varies seasonally, it might be possible to selectively retain, or remove, one nutrient by altering the discharge depth seasonally. For example, if it was desirable to retain more nitrate than phosphorus in Lake Mead, this could probably be achieved by operating Hoover Dam with epilimnion discharge in the summer. Similarily, more phosphorus could be retained in the spring with an epilimnion discharge. Over a long-term period, continous operation from either an epilimnion or hypolimnion discharge could be expected to have a pronounced effect on the nutrient and possibly trophic status of Lake Mead.

We have developed a fairly simple model to illustrate how altering the discharge depth could affect the nutrient status of a reservoir (Paulson and Baker 1978,1979a). In order to build this model, it was necessary to make a number of simpli-fying assumptions (Fig. 5.4.2), and some of these could be criticized as being unrealistic. Nevertheless, the most crucial assumption is that 90% of the nutrients in the euphotic zone are utilized by phytoplankton which sink to the hypolimnion and are decomposed to release nutrients. Although the exact values may be incorrect, it is clear that this assumption is valid for nitrate in Lake Mead. Changing the other assumptions
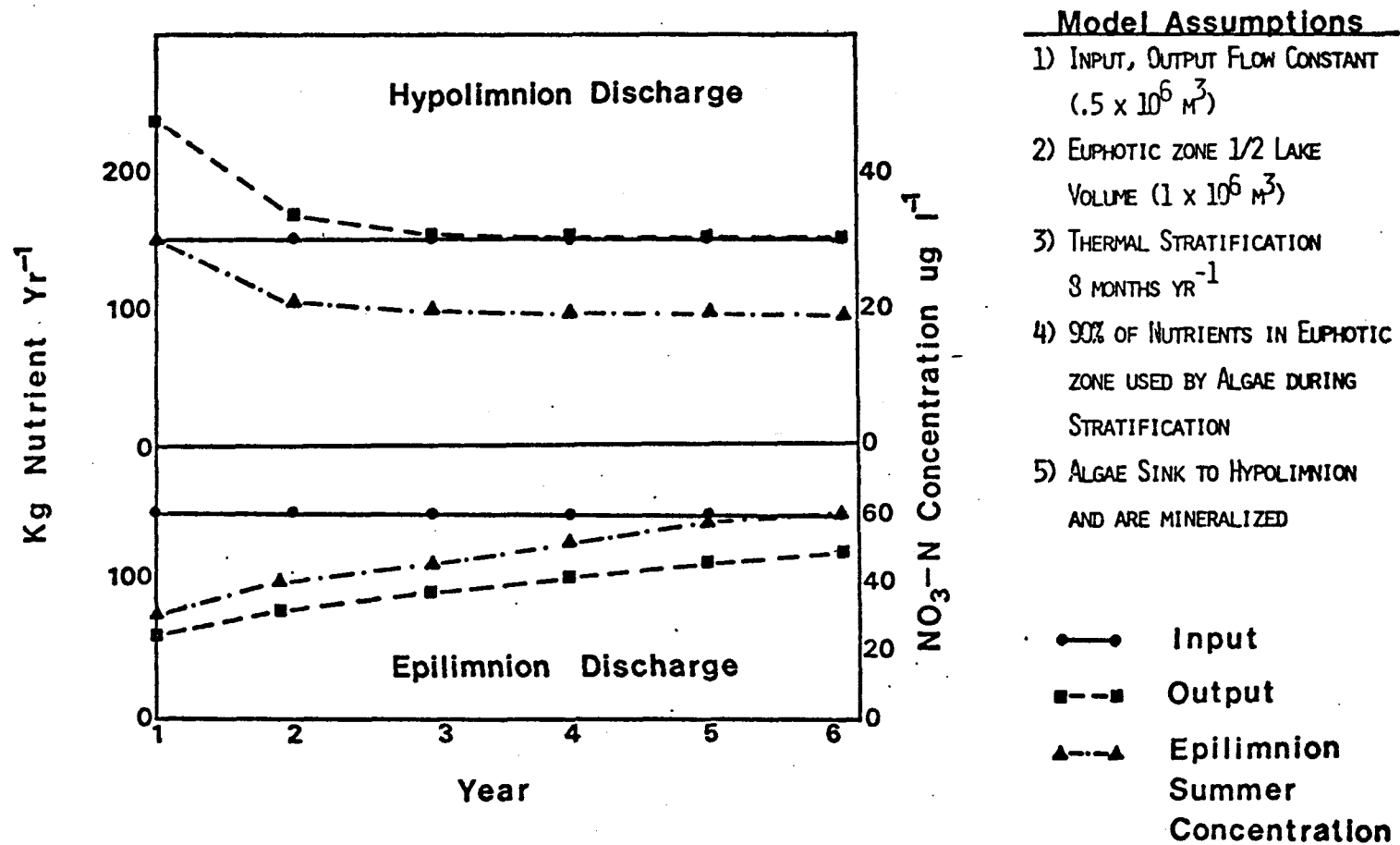
Figure 5.4.2   Model of nutrient loss for epilimnion and hypolimnion discharge for a reservoir.

will accelerate or delay the rate at which the reservoir reaches nutrient equilibrium, but this will not alter the basic pattern that is illustrated by the model.

If water is discharged from the nutrient-rich hypolimnion, the reservoir progressively loses nutrients but eventually reaches an equilibrium at a lower nutrient concentration (Fig. 5.4.2). Conversely, if water is discharged from the nutrient-poor epilimnion, the reservoir accumulates nutrients, and an equilibrium is reached at higher nutrient concentrations. The trends predicted by the model have been observed in experiments conducted on Kortowskie Lake, Poland, under different discharge regimes (Mientke and Mlynska 1977). Annual nitrogen and phosphorus retention in Kortowskie Lake was 28% and -10% respectively, for hypolimnion discharge but increased to 36.2% and 65.9%, respectively, for epilimnion discharge. Hypolimnion discharge is currently being used to restore the water quality of this lake and protect it against excessive eutrophication in the future (Sikorowa 1977).

Wright (1967) contends that the progressive loss of nutrients via hypolimnion discharge may, in part, explain why the phytoplankton productivity of reservoirs often decreases with time. Although there is debate whether this is generally true for all reservoirs (Silvey and Stanford 1978). Martin and Arneson's (1978) limnological comparison of a surface discharge lake and deep discharge reservoir on the Madison River supports Wright's hypothesis. It appears that nutrient retention, and possibly productivity could also be manipulated in Lake Mead by moving the depth of discharge.

However, several other factors must be investigated before this can be used for manipulation of nutrients and water quality management of the reservoir.

First, our nutrient budget model was based on soluble nutrient concentrations (e.g. nitrate, ammonia, phosphate), but this must be balanced against organic and total nitrogen and phosphorus concentrations in the reservoir. If, for example, soluble nitrogen accumulated to 100 $\mu g \cdot 1^{-1}$ in the hypolimnion, but organic nitrogen remained at 100 $\mu g \cdot 1^{-1}$ in the epilimnion, then moving the depth of discharge would change the chemical form, but not the total amount of nitrogen lost from the reservoir.

Alterations in the depth of discharge can also influence other physical and chemical factors. Reservoirs with epilimnion discharge tend to dissipate heat, whereas those with hypolimnion discharge store heat (Wright 1967, Martin and Arneson 1978). Oxygen concentration in the epilimnion does not vary appreciably with discharge depth, but oxygen in the hypolimnion is typically lower in reservoirs with epilimnion discharge (Stroud and Martin 1973). These factors have a direct effect on distribution of fish and other aquatic organisms and must be carefully considered in designing or modifying hydroelectric facilities.

Finally, altering the depth of discharge can have an immediate impact on the limnological conditions of the river and reservoirs downstream. Enrichment of downstream reservoirs is fairly common with hypolimnion discharge (Neel 1963). The upper reaches of Lake Mohave are extremely productive due to

discharge of water high in nitrogen from the hypolimnion of Lake Mead. Similarly, Martin and Arneson (1978) reported that Quake Lake was highly productive due to input of nutrient-rich water from an upstream reservoir. Conversely, the productivity of downstream reservoirs could decrease if epilimnion discharge resulted in a decrease in nutrient loss from the upstream reservoir.

We currently have a proposal submitted to the Office of Water Research and Technology to investigate the impacts of altering discharge depth on the reservoirs on the Colorado River (Paulson, Deacon and Baker 1979). This study will enable us to better define the relationship between operation of hydroelectric facilities and nutrient status of the reservoirs. However, it seems clear that hydroelectric facilities have potential for managing the nutrient and trophic status of reservoirs, as well as for power generation.

5.4.2 Lake Mohave

Generally, both chlorophyll-a and phytoplankton productivity were higher in Lake Mohave than in Lake Mead, except for Las Vegas Bay. This was primarily due to high nutrient inputs derived from the hypolimnion of Lake Mead.

Based an annual average chlorphyll-a concentration, the main lake stations in Lake Mohave were mesotrophic. Chlorophyll-a concentrations ranged from 2-6 $\mu g \cdot l^{-1}$ throughout the year which is in the low range of values given for mesotrophic lakes. There was only one occasion when chlorophyll-a was extremely high (49.6 $\mu g \cdot l^{-1}$), and this occurred at Eldorado Canyon on 11 May, 1977 when the cold water-warm

water interface was located at this station. It was evident from visual observations that chlorophyll-a concentration was highly variable at Eldorado Canyon, depending on the location of the convergence.

Average daily productivity in Lake Mohave was in the eutrophic range. This was caused by relatively high productivity in the winter at the down-lake stations where productivity was usually greater that 400 mg $C \cdot m^{-2} \cdot day^{-1}$. Maximum daily productivity at these stations was comparable to maximums in temperate lakes classified as mesotrophic (Wetzel 1975). However, the high winter productivity increased average daily productiviey for the year. Productivity at Eldorado Canyon ranged from 53 - 2976 mg $C \cdot m^{-2} \cdot day^{-1}$ and was similar to temperate lakes classified as eutrophic (Wetzel 1975). Therefore, the trophic state of Lake Mohave, based on productivity, was intermediate between mesotrophic to eutrophic.

Total phosphorus loading reported by EPA (1978b) would place Lake Mohave in an extremely eutrophic state. However, as in Lake Mead, this was not evident by the other trophic indicators. EPA (1978b) noted that phosphorus loading models might not be applicable to reservoirs with very short hydraulic retention times. Such is the case in Lake Mohave where the hydraulic retention time averages about 80 days. Total phosphorus concentration in the lake ranged from 2-27 $\mu g \cdot l^{-1}$ (Priscu 1978), which was similar to mesotrophic lakes (10-30 $\mu g \cdot l^{-1}$) reported by Likens (1975). Thus by Likens' (1975) criteria, Lake Mohave would be mesotrophic on the basis of total phosphorus, not eutrophic as the total phosphorus loading models would predict.

5.4.3 Effect of Phosphorus Removal on the Inorganic Phosphorus
Concentration in the Lower Basin and Lake Mohave.

There has been considerable controversy over the opera-
tion of an Advanced Wastewater Treatment Plant (AWT) in Las
Vegas to remove phosphorus from sewage effluent discharged into
Las Vegas Bay. Proponents of the plant claim it is necessary
to reduce the phosphorus concentration of the Las Vegas Wash
inflow to 0.5 $mg \cdot 1^{-1}$ to control phytoplankton growth in Las
Vegas Bay. Others maintain that the current levels of phy-
toplankton in the bay do not pose a serious problem and there
is no need for such extreme treatment. Our investigation was
not designed to evaluate the need for AWT, but we did collect
limnological data that can be used to assess the effectiveness
of the plant in reducing the phosphorus concentration in the
Lower Basin, and the influence this will have on the limnology
of Lake Mead and Lake Mohave.

The Las Vegas Wash inflow contributed 136.6 x 10^3 kg of
inorganic phosphorus to the Lower Basin from October, 1977 to
September, 1978. Another 29.8 x 10^3 kg was derived from the
Colorado River via Boulder Canyon. Of these inputs, 33.8%,
or 56.2 x 10^3 kg, was retained in the basin, and the remainder
(110.0 x 10^3 kg) was discharged downstream to Lake Mohave.
The average monthly concentration of inorganic phosphorus
in Las Vegas Wash was 1.8 $mg \cdot 1^{-1}$, and the discharge at Hoover
Dam averaged 12 $\mu g \cdot 1^{-1}$. The water discharge averaged 6.3 x
10^6 $m^3 \cdot month^{-1}$ in Las Vegas Wash and 7.7 x 10^8 $m^3 \cdot month^{-1}$ at
Hoover Dam.

An estimate of the monthly change in phosphorus concen-

tration in the Lower Basin under reduced loading from Las Vegas
Wash can be derived from equation (1).

$$\Delta P = \frac{(I_{LVW} + I_{BC}) - R - 0}{V} \, k_1 \text{--} k_n \qquad (1)$$

Where ΔP = change in phosphorus concentration of the Hoover

Dam outflow ($\mu g \cdot 1^{-1} \cdot month^{-1}$)

I_{LVW} = phosphorus input from Las Vegas Wash ($kg \cdot month^{-1}$)

I_{BC} = phosphorus input from Boulder Canyon ($kg \cdot month^{-1}$)

R = phosphorus retention in Lower Basin ($kg \cdot month^{-1}$)

0 = phosphorus output at Hoover Dam. ($kg \cdot month^{-1}$)

V = volume in Lower Basin at various lake levels (m^3)

$k_1 \text{--} k_n$ = unit conversion factors

In using this equation we assumed that:

(i) I_{LVW} was 3.2×10^3 $kg \cdot month^{-1}$ (.5 $mg \cdot 1^{-1}$ at average water
      discharge of 6.3×10^6 $m^3 \cdot month^{-1}$), the projected phos-
      phorus load in Las Vegas Wash from the AWT.

(ii) I_{BC} was 2.5×10^3 $kg \cdot month^{-1}$, the current phosphorus
      load from Boulder Canyon.

(iii) R was 33.8% of. the phosphorus inputs, the current rate
      of inorganic phosphorus retention in the Lower Basin.

(iv) 0 would initially be 9.2×10^3 $kg \cdot month^{-1}$ (12 $\mu g \cdot 1^{-1}$ at
      7.7×10^8 $m^3 \cdot month^{-1}$ average water discharge) but would
      then decrease each month as the phosphorus concentration
      changes in the outflow.

(v)   V would be the volume of water in the Lower Basin for
      elevation 1100 ft. (5.6×10^9 m^3), 1150 ft. (7.2×10^9 m^3)

and 1190 ft. (8.6 x 10^9 m^3).

We then computed the monthly change in phosphorus concentration and subtracted this from the actual concentration in the previous month. These variables were computed for a 24-month period of reduced phosphorus loading from Las Vegas Wash.

The phosphorus concentration in the outflow at Hoover Dam would decrease in an exponential manner from an initial concentration of 12 $\mu g \cdot l^{-1}$ to approximately 5 $\mu g \cdot l^{-1}$, depending on lake elevation, in a 24 month period (Fig. 5.4.3). The phosphorus concentration would be slightly lower at lower lake elevations. This is the opposite of what would be expected due to the dilution of the Las Vegas Wash inflow at higher lake elevations. Higher lake elevations do cause more dilution of the inflow, but this is masked by the enormous influence of the discharge at Hoover Dam.

A monthly phosphorus load of 3.2 x 10^3 kg from Las Vegas Wash would increase the concentration in the entire Lower Basin by .67, .52 and .44 $\mu g \cdot l^{-1}$, respectively, at lake elevations of 1100 ft., 1150 ft. and 1190 ft., clearly showing the dilution effect. However, a monthly phosphorus output of 9.2 x 10^3 kg at Hoover Dam would decrease the concentration by 1.64, 1.27 and 1.06 $\mu g \cdot l^{-1}$ at these same lake elevations. The slight increase in concentration at lower lake elevations becomes significant when multiplied by the high rate of discharge. The phosphorus loss in the discharge increases accordingly and, in turn, causes a greater decrease in the phosphorus concentration at lower lake elevations.

It has been theorized that the low lake elevations in the
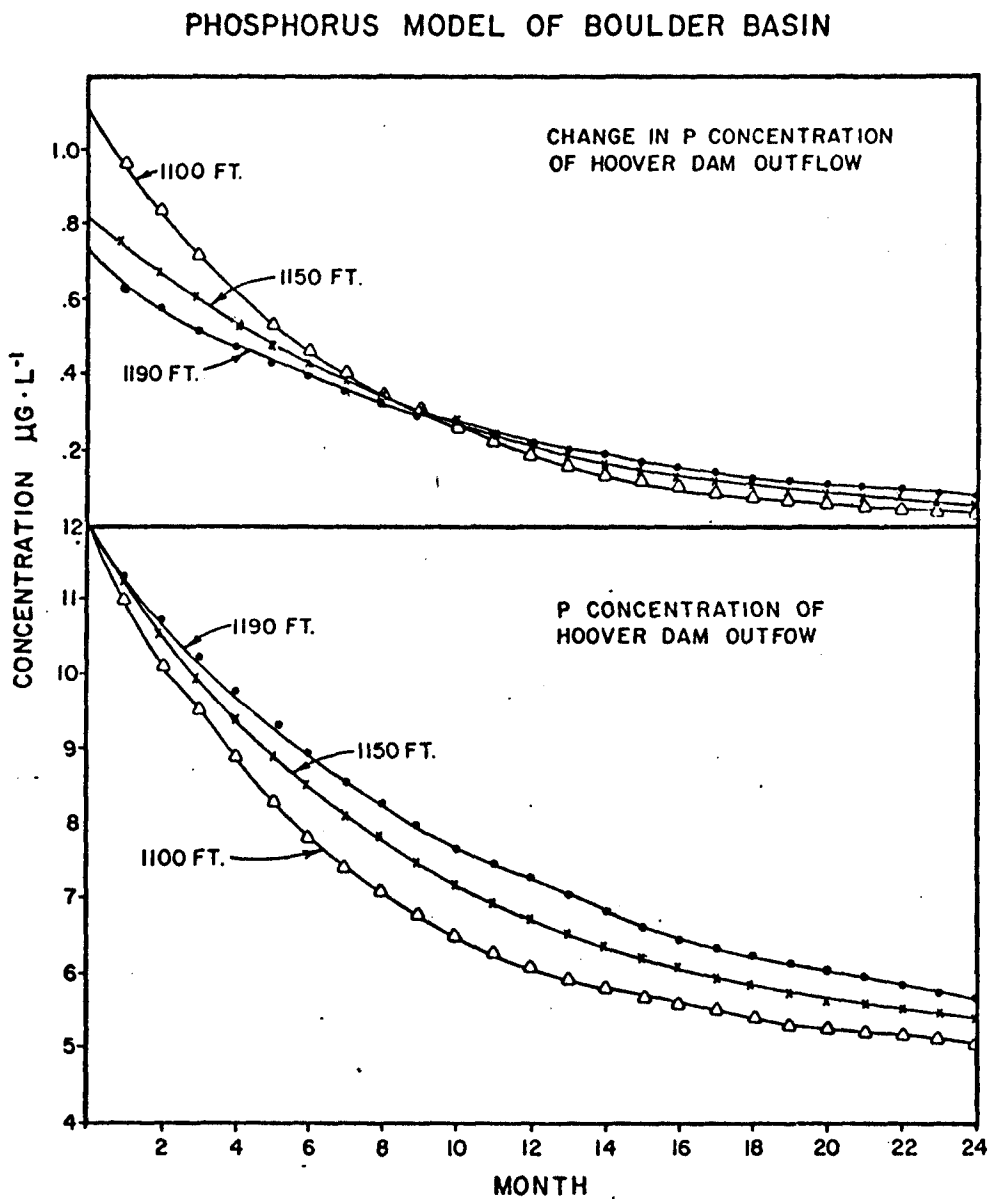
PHOSPHORUS MODEL OF BOULDER BASIN

Figure 5.4.3 Phosphorus model of Boulder Basin.

period from 1968 - 1974 caused the degradation of water quality
in Las Vegas Bay. This does not appear to be the case since
phosphorus discharge from the dam overrides the dilution effect
relative to these changes in lake elevation. Even in the inner
Las Vegas Bay, where phytoplankton growth is highest, it appears
that changes in lake elevation will not appreciably alter
dilution of the Las Vegas Wash inflow.

Dilution of the inflow varies with the degree of lateral
mixing, which is determined by surface area, and vertical mixing,
which is determined by depth. The inner bay is canyon-like
and changes in lake elevation are not accompanied by large
changes in surface area. Moreover, for most of the year, the
density current flows along the bottom in the deepest part of
the old wash-channel, and there is minimal lateral mixing of
the inflow. Vertical mixing, therefore, is the principal
mechanism of dilution, but, regardless of lake elevation, com-
parable mixing should occur at comparable depths in the inner
bay (Fig. 5.4.4). For example, vertical mixing and the rate
of dilution at Station A for an elevation of 1180 ft. should
be comparable to that for Station B for an elevation of 1150 ft.
(Fig. 5.4.4). Thus, there is no real change in the absolute
dilution rate so long as the point of measurement is shifted
to compensate for changes in lake elevation. Similarly, the
degree of nutrient availability and phytoplankton growth should
not change appreciably with lake elevation. The zone of maximum
phytoplankton growth will simply advance or recede in the inner
bay as lake elevation increases or decreases. For example in
1968, at an average lake elevation of 1120 ft. this zone was

The principal impact of reduced phosphorus loading from
operation of the AWT plant will be a significant reduction in
the phosphorus load discharged to Lake Mohave, and a decrease
in phosphorus concentration to low levels in the Lower Basin,
except for areas in the Inner Las Vegas Bay. Chlorophyll
concentration should decrease accordingly which will reduce
the trophic status of most of the Lower Basin and Lake Mohave
to an oligotrophic state. The Inner Las Vegas Bay will prob-
ably remain in a mesotrophic-eutrophic state.

Further reductions in the trophic status of Lake Mead
and Lake Mohave may be detrimental to the sport fisheries in
these reservoirs. The reservoirs are currently used exten-
sively by fishermen and it seems that some consideration should
be given to maintaining sufficient fertility in these systems
to produce a quality sport fisheries. The largemouth bass
fishery in Lake Mead has undergone a significant decline since
formation of Lake Powell and this may be related to changes in
fertility of the reservoir over this period (Paulson et al.
1979). It was suggested as early as 1954 that the bass fishery
in Lake Mead could probably be improved by fertilization. This,
however, has never been done due to the enormous cost and con-
stant need for refertilization. However, nutrients contained
in wastewater could provide a constant supply of low-cost
fertilizer and, therefore, prove beneficial in improving the
bass fishery in Lake Mead.

5.5 Influence of Power Modifications on Limnological Status

5.5.1 Lake Mead

The U.S. Bureau of Reclamation is currently con-

sidering several alternatives for increasing peak-power output from Hoover Dam. These alternatives include: (a) upgrading the existing generating units and, (b) replacing one or more conventional generating units and (c) adding reversible, pump-storage hydroelectric units (USDI 1978). These modifications will involve alterations in the existing discharge that, in turn, will influence the limnological status of Lake Mead and Lake Mohave.

The monthly discharge cycle from Hoover Dam is bimodal with peaks occurring in April and August (Fig. 5.5.1). Minimum monthly discharge usually occurs in January. A typical weekly cycle during summer, the period of maximum power demand, is depicted in Fig. 5.5.2. Discharge is lowest on weekends but then increases progressively to a maximum on Wednesday or Thursday. The typical daily discharge cycle in the summer fluctuates from a minimum of 2-3,000 $ft^3 \cdot sec^{-1}$[*] in early morning to a maximum of 25-30,000 $ft^3 \cdot sec^{-1}$ between mid-afternoon and dusk (Fig. 5.6.3). The proposed power modifications will not seriously alter the monthly or weekly discharge cycle at Hoover Dam. However, there will be significant changes in the daily discharge pattern.

Currently, the discharge rarely exceeds 30,000 $ft.^3 \cdot sec^{-1}$ or drops below 2000 $ft.^3 \cdot sec^{-1}$ during a daily power cycle. Upgrading of existing generators (alternative A), will require a minimum discharge of about 2000 $ft.^3 \cdot sec^{-1}$ during the week, and a maximum of 49,000 $ft.^3 \cdot sec^{-1}$ by mid-week (Fig. 5.5.4)

[*]English units are used in this section of the report at the request of the U.S. Bureau of Reclamation.
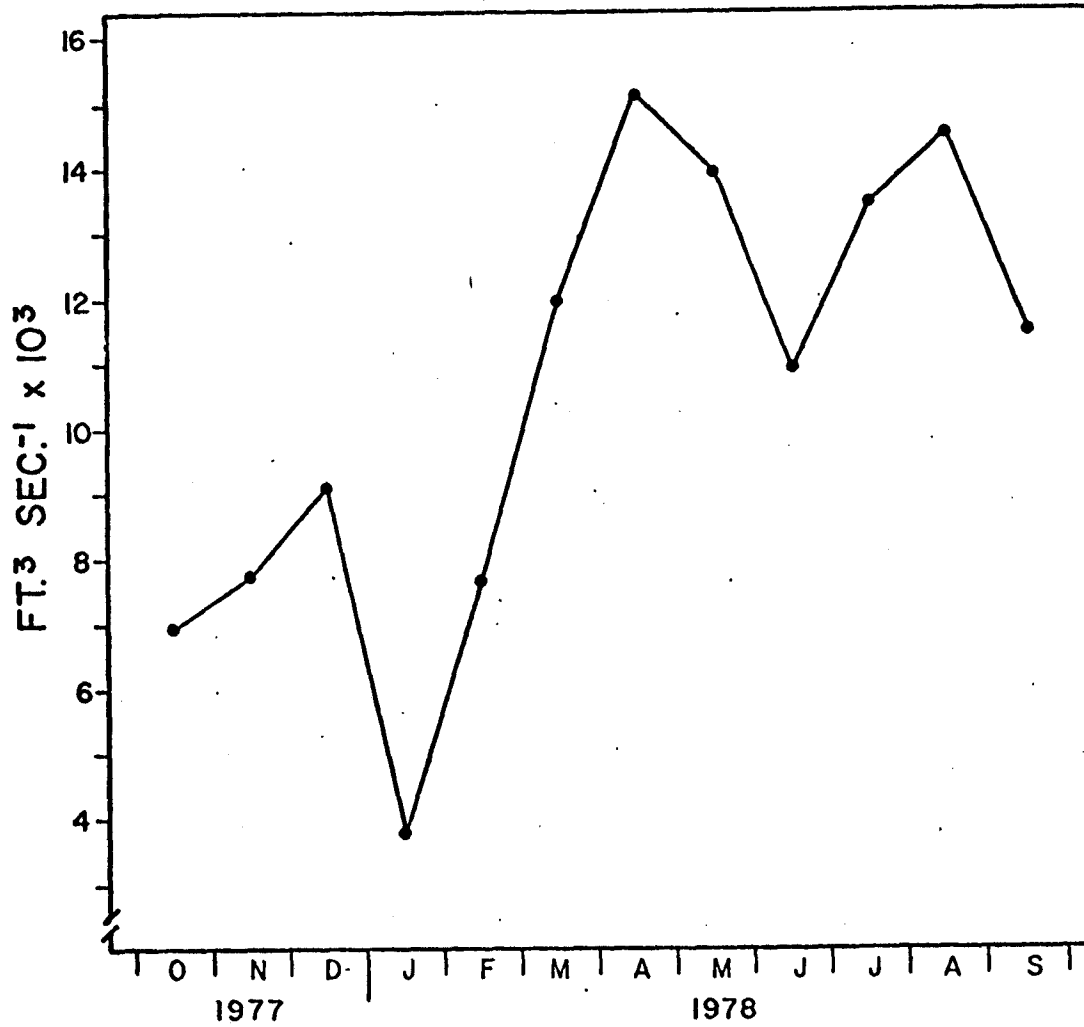
Figure 5.5.1   Monthly discharge pattern for Hoover
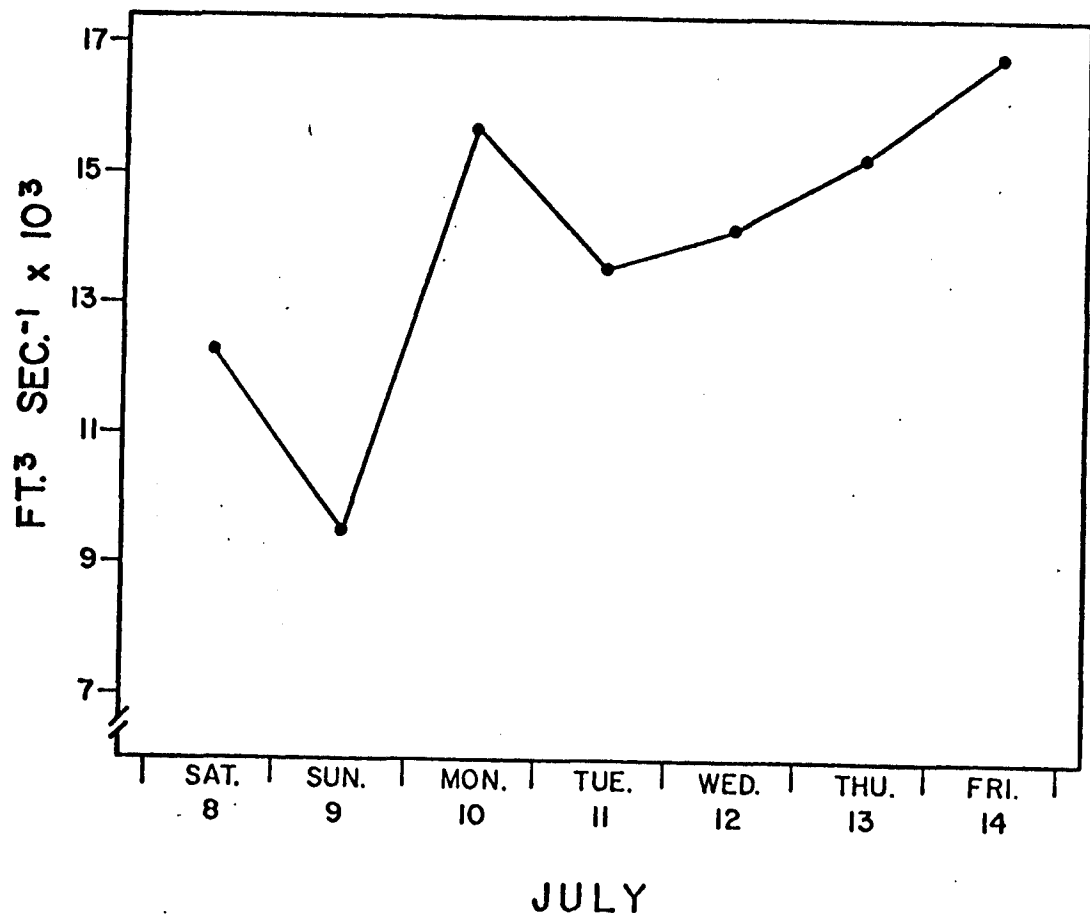   Dam.

Figure 5.5.2   Weekly discharge pattern for Hoover Dam.

(Table 5.5.1). Replacement of existing generators (alternative B), will require a minimum discharge of about 2000 ft.$^3 \cdot$sec^{-1} and a maximum discharge of 56,000 ft.$^3 \cdot$sec^{-1} by mid-week (Fig. 5.5.5) (Table 5.5.1). Installation of reversible pump-storage units (alternative C) will increase the peak discharge to a maximum of 76,000 ft.$^3 \cdot$sec^{-1} by mid-week and require reverse flow of 25,000 ft.$^3 \cdot$sec^{-1} during the week (Fig. 5.5.6) (Table 5.5.1). There will also be periods of no flow for this alternative. These alterations in discharge will have a direct influence on the current patterns and temperature structure up-lake from Hoover Dam and in Lake Mohave.

The origin of replacement water for the discharge from Hoover Dam varies in relation to the rate and duration of discharge and lake temperature. A funnel-like withdrawal layer is created on a discharge cycle as replacement water is drawn from above, below and up-lake of the penstocks (Wunderlick and Elder 1973). In cross section, this withdrawal layer approximates that shown in Fig. 5.5.7 which was constructed from current measurements made at Hoover Dam in 1967 (Sartoris and Hoffman 1971). The current velocity is maximum at the discharge depth but then decreases above and below the penstocks. The depth of the withdrawal layer (d_1) will vary in relation to the rate of discharge, and the distance that it extends up-lake (d_2) will depend on the duration of the discharge cycle. The withdrawal layer, however, is further influenced by the temperature of the reservoir.

The density gradient that exists during thermal stratification can modify the upper limit of the withdrawal layer.

Table 5.5.1   Minimum and maximum discharge required for
proposed power modifications of Hoover Dam
(U.S. Bureau of Reclamation estimates).

Discharge	Alternative A	Alternative B	Alternative C
Maximum Flow ($ft^3 \cdot sec.^{-1}$)	49,000	56,000	76,000
Minimum Flow ($ft^3 \cdot sec.^{-1}$)	2,000	2,000	-25,000*
Megawatt Capacity	1,810	2,070	2,800

Alternative A, B = upgrading and/or replacement of conventional
                    generating units.

Alternative C = reversible, pump-storage generating units.

*Maximum reverse discharge
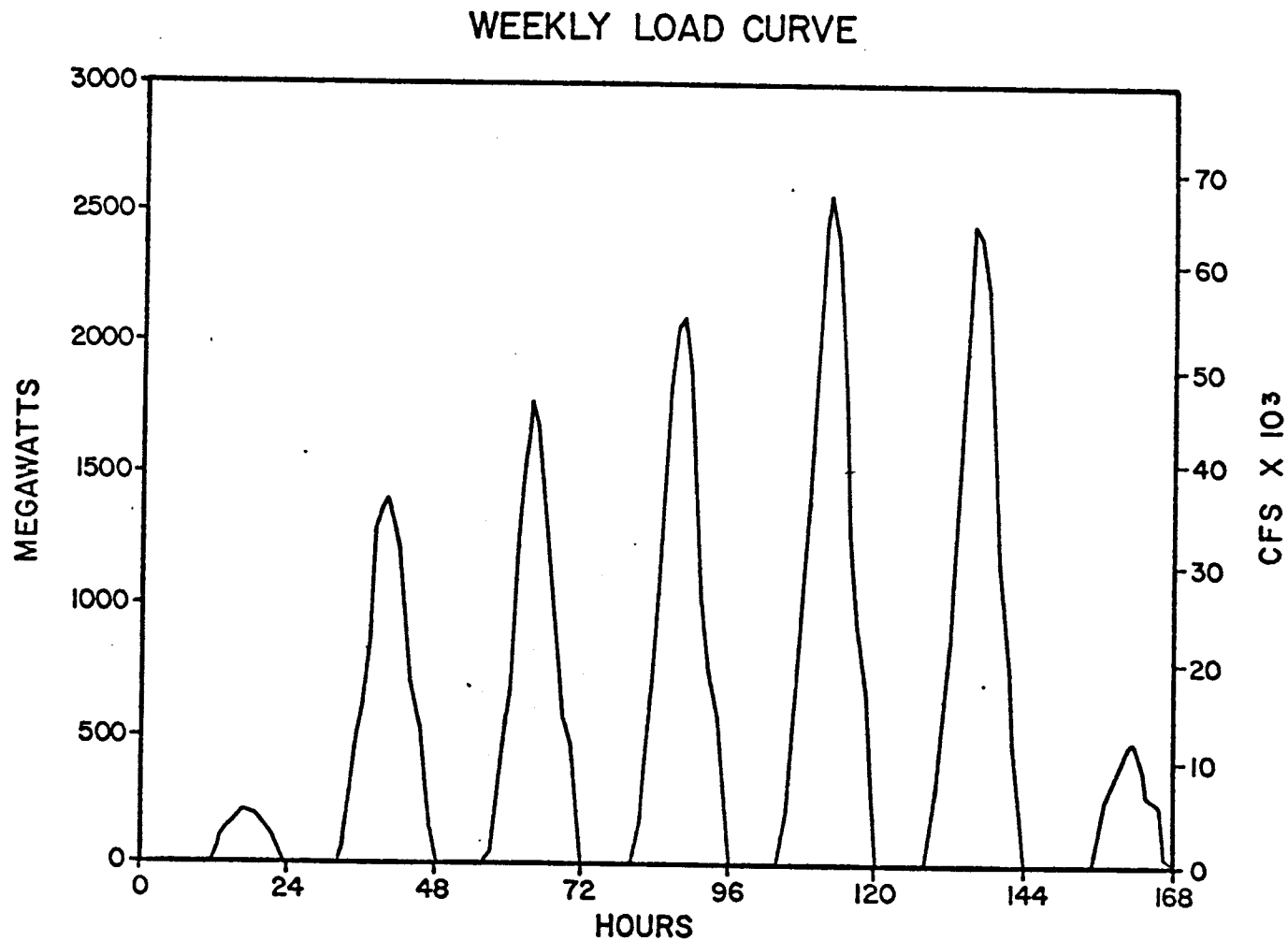
WEEKLY LOAD CURVE

Figure 5.5.5   Typical weekly discharge cycle for alternative B, power modification to Hoover Dam.
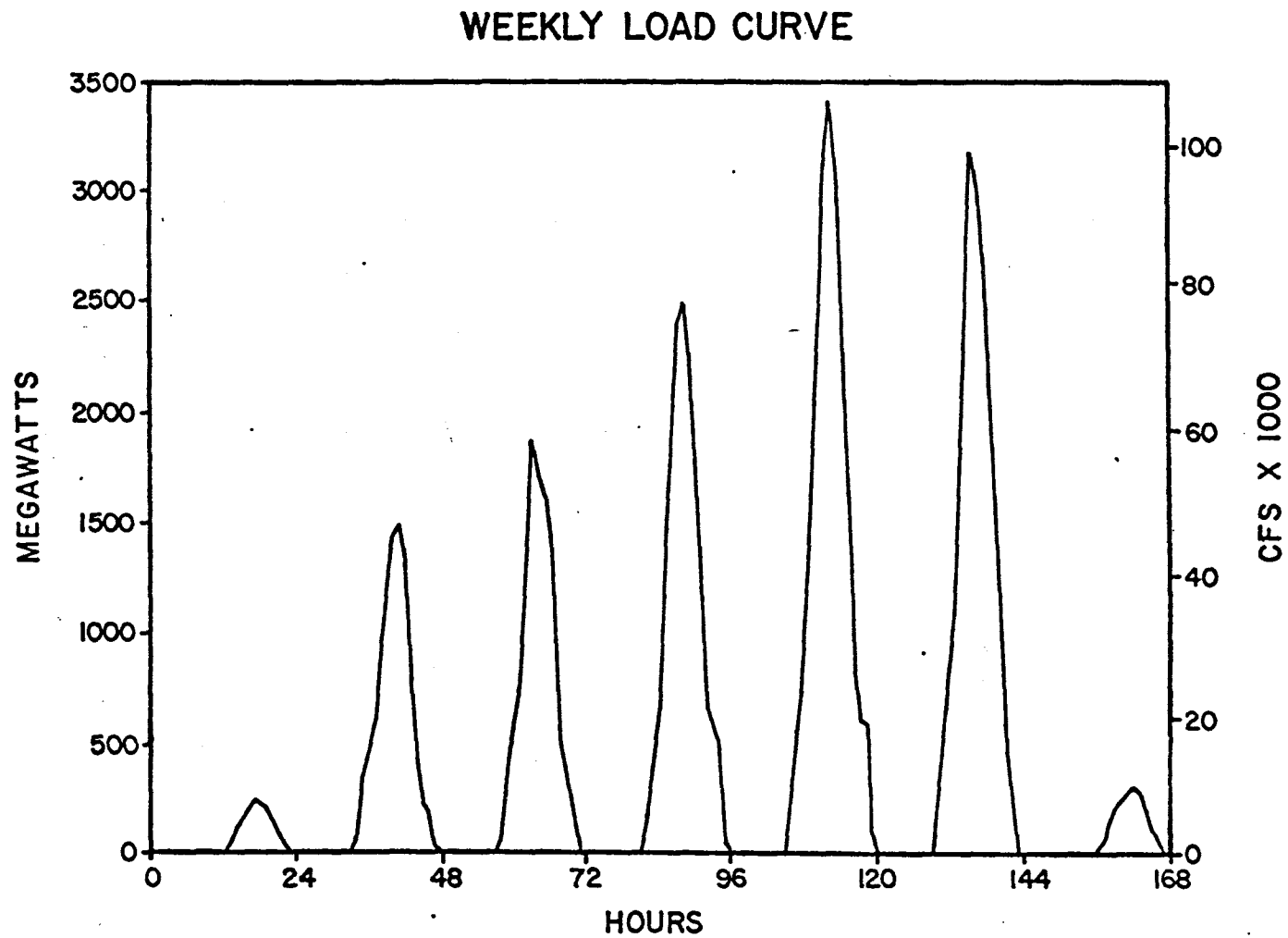
WEEKLY LOAD CURVE

Figure 5.5.6 Typical weekly discharge cycle for alternative
C, power modification to Hoover Dam.
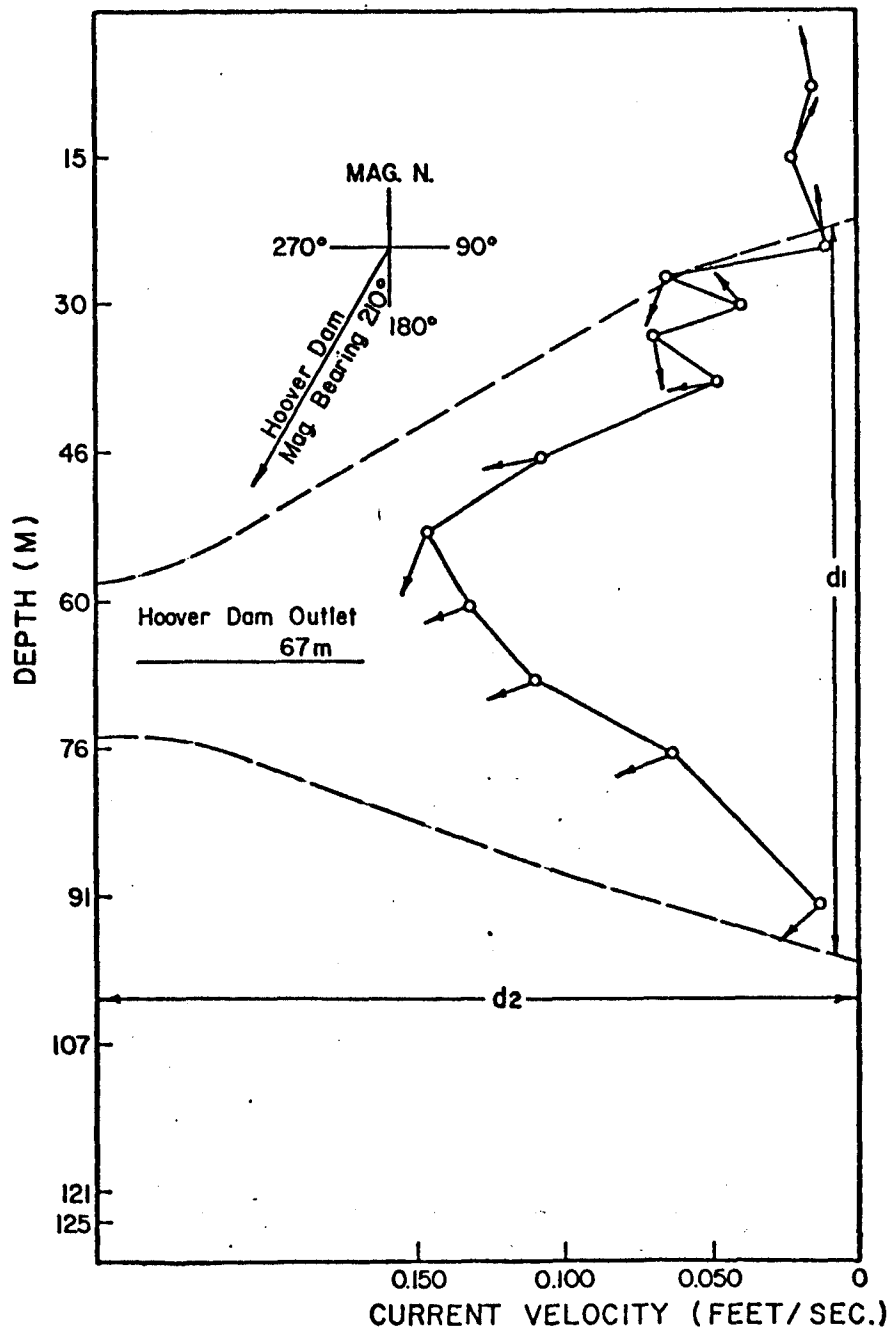
Figure 5.5.7   Theoretical withdrawal layer
              generated by discharge from
              Hoover Dam.

Warm water is less dense than cold water, and, therefore, as lake temperature increases, it becomes progressively more difficult to draw replacement water from overlying, warmer strata near the dam. Unless the discharge is high enough to overcome the density gradient, replacement water is drawn from the hypolimnion up-lake from the dam. The temperature of the discharge from Hoover Dam rarely exceeds that in the hypolimnion (12.5°C), indicating that the current rate of discharge is not sufficient to draw warmer, overlying water to the penstocks. However, the alternative power modifications proposed for Hoover Dam will all require discharge greater than the current levels which will modify the temperature structure near the dam.

The maximum discharge on day 5 of a weekly cycle will range from 49,000 ft.$^3 \cdot$sec^{-1} for alternative A to 76,000 ft.$^3 \cdot$sec^{-1} for alternative C. These higher rates of discharge will produce a temperature structure near the dam similar to that depicted in Fig. 5.5.8a,b,c. At progressively higher maximum discharge, the withdrawal layer will expand into the upper-hypolimnion which will tend to pull down the temperature isotherms in the upper-hypolimnion and metalimnion.

The temperature isotherms will start to return to a normal position, due to the natural tendency of warmer water to rise, as the discharge decreases at the end of a power cycle. However, as the hypolimnion water mass that was set in motion down-lake on the power cycle collides with the dam, the temperature isotherms will be displaced toward the surface (Fig. 5.5.8a,b). The daily alternation of high and low dis-
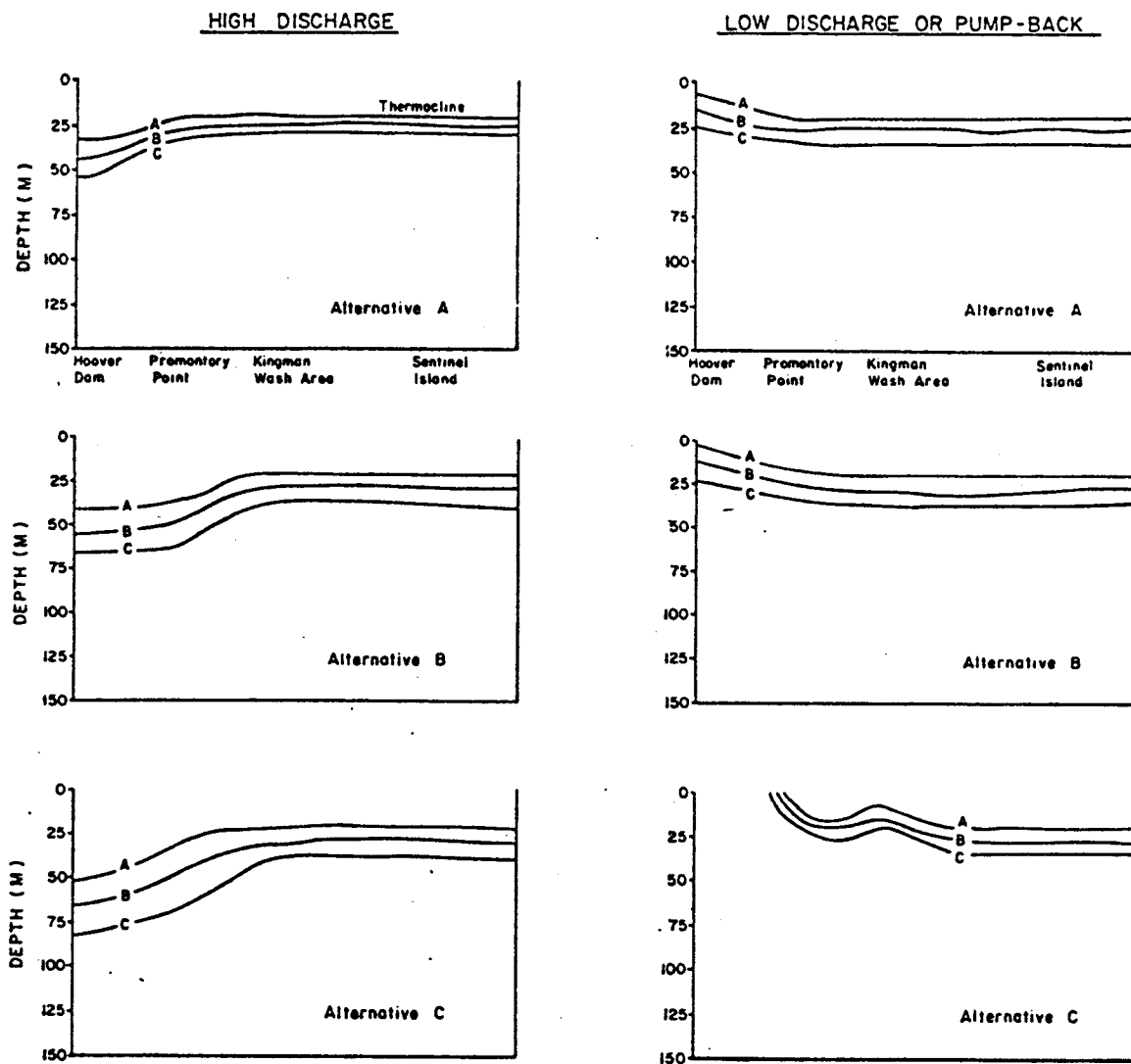
Figure 5.5.8   Temperature isotherms in Black Canyon, Lake Mead for high and low discharge from Hoover Dam.

charge will thus create some temperature instability, similar to the rocking motion produced by a wind-induced seiche.

It is difficult to predict how far this temperature instability will extend up-lake from the dam. This, however, will largely depend on the duration of the power cycle. The volume of water in the epilimnion and hypolimnion of Black Canyon, Kingman Wash and Boulder Basin, south of Sentinel Island, is presented in Table 5.5.2. Each of the proposed power modifications will require a maximum daily discharge during mid-week (Table 5.5.2) in excess of the hypolimnion volume in Black Canyon. However, the volume of the Kingman Wash area and Black Canyon is sufficient to accommodate the daily discharge required for each alternative. Thus, the principal effects of the alterations in discharge should be confined primarily to Black Canyon. Up-lake from there the volume increases significantly and will buffer the effects of the daily power cycles from Hoover Dam. The temperature and current patterns in Boulder Basin are presently influenced by discharge from Hoover Dam but only after extended periods of high discharge in the summer. Since there will be no appreciable change in the total weekly or monthly discharge with any of the power modifications, the temperature and current patterns in Boulder Basin and elsewhere in Lake Mead should not change appreciably as a result of alternating high and low daily discharge.

The addition of reversible, pump-storage units to Hoover Dam (alternative C) will have a more pronounced influence on the temperature structure and current patterns near the dam.

Table 5.5.2   Epilimnion and hypolimnion volume for Black Canyon,
Kingman Wash area and Boulder Basin (south of
Sentinel Island). (U.S. Bureau of Reclamation
estimates).

Depth Strata (ft.)	Volume (ac.-ft.)		
	Black Canyon	Kingman Wash	Boulder Basin
Epilimnion (1180'-1130')	6,000	22,000	23,000
Hypolimnion (1130'-730')	38,000	80,000	102,000
Total (1180'-730')	44,000	102,000	125,000

In addition to requiring 76,000 ft.$^3\cdot$sec^{-1} of maximum discharge, this alternative will necessitate daily reverse flow of 25,000 ft.$^3\cdot$sec^{-1} for 6 hours, or a total of 12,396 ac.ft.$^3\cdot$day^{-1}. Minckley and McNatt (1976) and McNatt (1976) conducted an investigation of the effects of reversible, pump-storage generating units on the temperature structure and currents in Canyon Lake, Arizona. They found that the temperature structure up-lake from Mormon Flat Dam was severely disrupted during the pumping cycle. The pumped-water surfaced as an upwelling near the dam where it encountered the canyon walls and the water mass moving down-lake from the previous discharge cycle. Further up-lake, the pumped-water forced back surface water but eventually dispersed back into depths where the pumped-water was at equal density with lake-water. They found that thermal restratification occurred fairly rapidly after a single pumping cycle. However, the thermal structure near the dam was continuously disrupted under prolonged pump-back operation.

Canyon Lake is similar to Lake Mead in that the dams are located in narrow canyons, but they differ with regard to discharge depth. The penstocks are located at 18 m at Mormon Flat Dam, relative to a total depth of 38 m; compared to 83 m at Hoover Dam, relative to a total depth of 140 m. The maximum volume of pumped-water at Mormon Flat Dam was 2,500ac. ft.$\cdot$day^{-1}, and that proposed for Hoover Dam will be 12,396 ac. ft.$\cdot$day^{-1}. However, the volume of pumped-water relative to depth of the penstocks and total depth will be similar at each dam. Therefore, temperature changes similar to those

observed by Minckley and McNatt (1976) will also occur in Black Canyon of Lake Mead.

The temperature isotherms in the upper hypolimnion will be pulled down toward the penstocks, and the cold hypolimnion water mass will start moving down-lake on the initial power cycle (Fig. 5.5.8c). On the pumping cycle, water will be forced back into the hypolimnion initially causing high turbulence near the penstocks. As the pumped-water collides with the hypolimnion water mass moving down-lake, an upwelling will occur forcing cold water toward the surface (Fig. 5.5.8c). This will elevate the epilimnion and metalimnion and possibly disrupt thermal stratification near the dam. The pumped-water will eventually reach a velocity sufficient to overcome the down-lake flow of the hypolimnion. When this occurs, the hypolimnion will be set in reverse motion and pushed back through Black Canyon into the Kingman Wash area. The pumped-water will then collide with the shelf that extends out from Kingman Wash, which will probably create another smaller up-welling in this area (Fig. 5.5.8c). After the pumping cycle, the upwellings will dissipate and the isotherms will start to return to their normal position. However, the temperature of water will be slightly colder and thermal stratification less stable than prior to the initial pumping cycle.

The isotherms will be pulled down even further on the second and successive power cycles because the temperature of overlying water will be colder, and less dense, than on the initial power cycle. Thus, more replacement water will be drawn from overlying strata near the dam. However, due to

the progressively greater discharge on each power cycle an
equal or greater volume of hypolimnion water will be drawn
down-lake than on the previous power cycle. Consequently,
upwelling will also occur at each successive pumping cycle
somewhere near the dam. The exact location and magnitude of
the upwelling will depend on how much replacement water is
pulled from the overlying strata versus that drawn down-lake
from the hypolimnion. As the down-lake flow of hypolimnion
water increases, so will the magnitude of the upwelling near
the dam.

The continual turbulence generated on the power and
pumping-cycles will, at the least, alter temperature and
currents in Black Canyon and Kingman Wash and, at the worst,
disrupt thermal stratification in these areas and possibly
in parts of Boulder Basin. Although the volume of pumped-
water is small by comparison to the volume in Boulder Basin,
south of Sentinel Island, it is the cumulative, rather than
instantaneous, effects of repeated pumping that will event-
ually alter limnological conditions up-lake from the dam.
The local effects of pumping will be greatest in Black Canyon
and Kingman Wash, but, after prolonged pump-back operation
during the summer, the temperature and current patterns are
likely to be disrupted well into Boulder Basin. This, as
well as the impact of alternatives A and B, will progressively
intensify as the lake level decreases below the current ele-
vation (1180 ft.). The depth of thermal stratification and
the temperature regime in Lake Mead are largely independent

of lake elevation. This is illustrated by temperature profiles taken at the Hoover Dam intake towers in July 1965, 1971, and 1978 when lake elevations were 1123 ft., 1150 ft., and 1180 ft., respectively (Fig.5.5.9). The temperature profiles are similar relative to depth from the surface. However, relative to a fixed point, like the depth of the intake gates, the temperature profiles change considerably with lake elevation.

Hoover Dam is equipped with intake gates at 1045 ft. (upper gates) and 900 ft. (lower gates) elevation. Currently, the dam is operated from the lower intake gates, but alternative A and B power modifications may require use of the upper gates. The maximum thickness of the withdrawal layer for each gate, as estimated from Sartoris and Hoffman (1971), is superimposed on the temperature profiles in Fig. 5.5.9. The discharge should not rise appreciably above 12-12.5°C on a power cycle so long as the dam is operated from the lower gates. However, if it does become necessary to use the upper gates, the discharge temperature will increase considerably, especially at lower lake elevation. For example, the discharge temperature would increase to at least 17.5°C (temperature at center of withdrawal layer) at a lake elevation of 1125 ft. (Fig. 5.5.9). Prior to 1953, when Hoover Dam was periodically operated from the upper gates, the discharge temperature frequently rose to 18-20°C by late summer and fall (Fig. 5.5.10). This occurred at an average monthly discharge of 18-20,000 ft.$^3 \cdot$sec^{-1} and peak-discharge of 30,000 ft.$^3 \cdot$

TEMPERATURE PROFILES AT HOOVER DAM
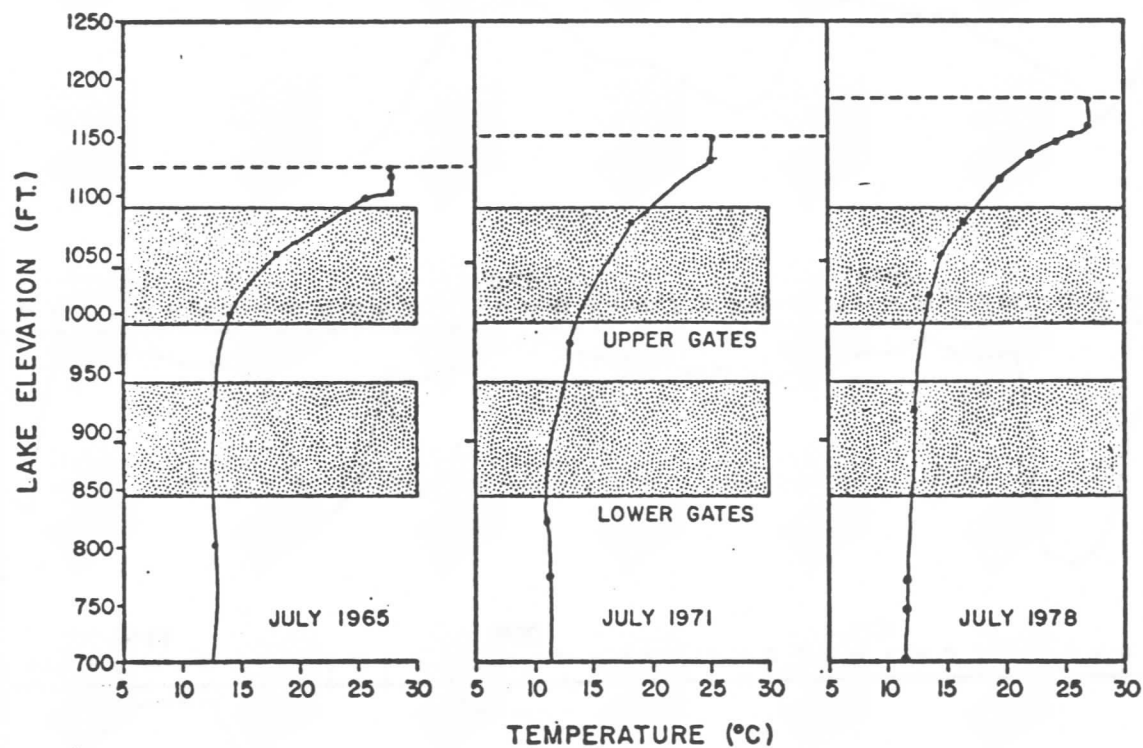## (U.S.G.S. DATA)

Figure 5.5.9 Temperature profiles versus lake elevation
in Black Canyon, Lake Mead.

AVERAGE TEMPERATURE OF HOOVER DAM DISCHARGE
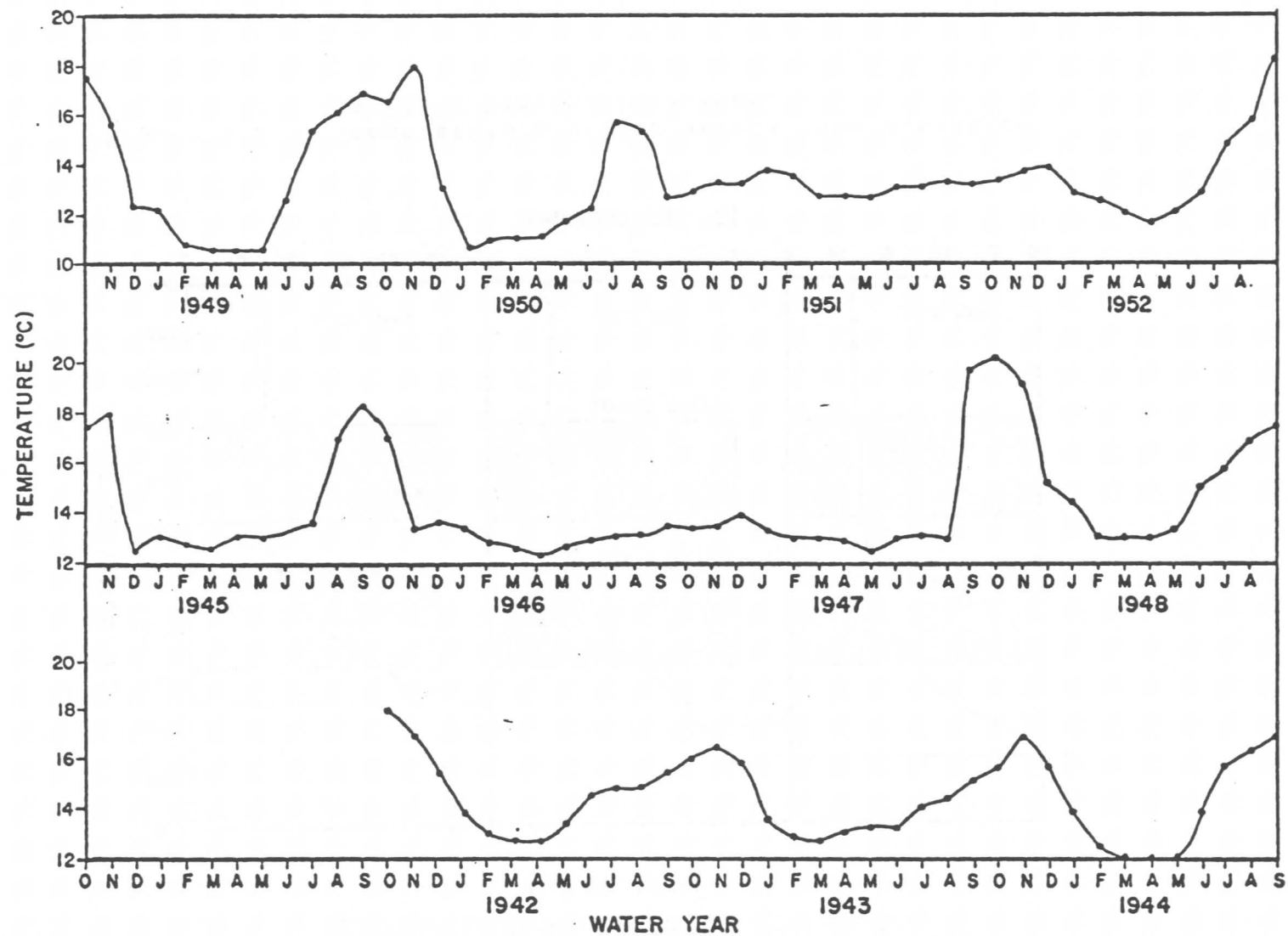
Figure 5.5.10 Temperature of discharge during operation from the upper and lower intake gates (USGS data).

sec^{-1}. The discharge temperature would increase even higher at the peak discharge required for the power modifications $(49,000-76,000 \ ft.^3 \cdot sec^{-1})$.

In addition to increasing the discharge temperature, operation of Hoover Dam from the upper gates will also cause oscillations of the thermocline, similar to those that will occur from use of the lower gates, during a power cycle. However, it appears that long-term use of the upper gates will not permanently alter the temperature structure of Lake Mead during the summer. Temperature profiles taken at the Hoover Dam intake towers during prolonged discharge from the upper gates (August-November, 1947 and June-November, 1952) and lower gates (June-November, 1946 and 1951) do show some difference in temperature between these periods (Fig. 5.5.11). However, these differences most likely reflect natural, year to year temperature variations rather than changes caused by alteration of the discharge depth. Thus, in Lake Mead, the major consequence of operating Hoover Dam at higher peak discharge, from either the upper gates or lower gates, will be the oscillation of the thermocline generated in the area near the dam.

Oscillations of the thermocline from alternating high and low discharge required for alternatives A and B will cause a slight increase in mixing of nutrients from the metalimnion to the epilimnion. This will also cause a slight increase in phytoplankton productivity, but the change will probably not be detectable without the aid of sensitive limnological monitoring equipment. However, upwellings caused by pump-

TEMPERATURE PROFILE AT HOOVER DAM

(U.S.G.S. DATA)
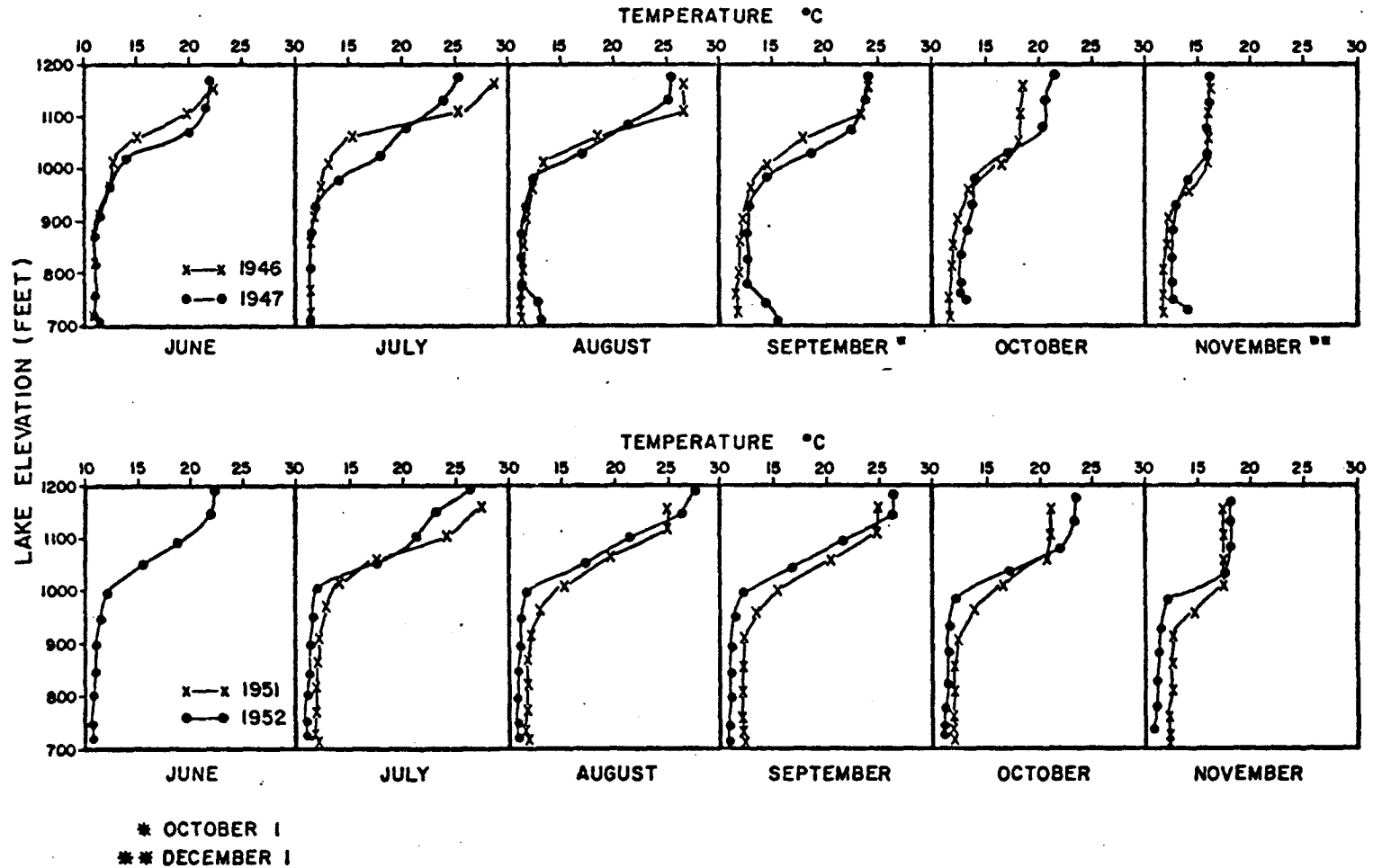
Figure 5.5.11   Temperature profiles in Black Canyon, Lake
Mead during operation from and upper and
lower intake gates.

back operations at Hoover Dam will recycle nutrients from
the hypolimnion to the epilimnion. This will significantly
enhance nutrients available for phytoplankton, and productiv-
ity will increase accordingly during the summer months.
The maximum productivity and chlorophyll-a that we measured at
Hoover Dam were 2362 mg $C \cdot m^{-2} \cdot day^{-1}$ and 6 $mg \cdot m^{-3}$, respectively
in September, 1978. This occurred when the thermocline dropped
by 5m and nutrients previously stored in the metalimnion were
mixed into the epilimnion. It is unlikely that the productiv-
ity or chlorophyll-a will increase much above these levels,
or that nuisance algal blooms will become more prevalent as
a result of pump-back operation. The turbulence and tempera-
ture changes caused by the upwelling of hypolimnion water will
create an extremely unstable environment in Black Canyon. This
will tend to limit the degree to which bloom-type conditions
can develop. Moreover, light penetration in the narrow canyon
is only comparable to other areas of the reservoir at mid-day.
In the morning and late-afternoon, the canyon walls shade most
of the open water which greatly reduces availability of light
for phytoplankton growth. Even at lower lake elevations, when
pump-back operations will intensify the upwellings (and nutrient
recycling), light and turbulence will limit further increases
in productivity. Therefore the proposed power modifications
will not cause any serious water quality problems to develop
in Lake Mead.

5.5.2 Lake Mohave

A very evident interface (convergence) develops in
Lake Mohave where cold, river-water discharged from Hoover

Dam underflows the surface water of Lake Mohave. The river-water is relatively high in nitrogen and phosphorus and mixing at the interface produces high phytoplankton productivity during the summer. Thus, a marked color difference is created between the river and lake-water which provides a means of monitoring the location of the interface.

The location of the interface changes in relation to discharge from Hoover Dam and water elevation in Lake Mohave. The interface is pushed down-lake at high discharge and recedes up-stream at low discharge. The interface extends further up-stream at high elevation in Lake Mohave and recedes down-lake at low lake elevation. During our investigation, the interface location varied from just below Willow Beach (mile 12.5) to Eldorado Canyon (mile 24) (Table 5.5.3).

This variation is caused by the extreme fluctuation of daily and weekly discharge from Hoover Dam and seasonal fluctuation in the water level in Lake Mohave. Typically, the interface extends furthest up-stream on weekends when the discharge from Hoover Dam is low.

We developed an equation to predict the location of the interface on the basis of 12 observations made during our investigation:

$$L = 4.63205 \; D \times 10^{-4} + 20399.2 \; \frac{1}{E} - 19.6726 \qquad \text{Equation (1)}$$

where: L = interface location (miles below Hoover Dam)

D = mean daily discharge from Hoover Dam $(ft.^3 \cdot sec^{-1})$

E = Lake Mohave elevation (ft.)

Table 5.5.3   Relationship between cold-warm water interface in Lake Mohave, daily discharge from Hoover Dam and Lake Mohave elevation.

Date	Interface Location (miles below Hoover Dam)		Average Daily Discharge $(ft^3 \cdot sec^{-1})$	Lake Mohave Elevation (ft)
	Observed	Predicted		
4 May 1977	24	18.0	18,200	645.7
14 June 1977	19	18.4	13,600	642.5
4 July 1977	14	14.3	4,010	636.1
5 July 1977	15	17.8	11,700	635.6
6 July 1977	23	21.0	18,500	635.5
28 July 1977	20.5	20.3	16,700	633.3
29 July 1977	21	22.2	21,000	633.6
8 August 1977	17.8	20.8	17,800	632.1
10 August 1977	21.5	20.6	17,200	632.4
25 August 1977	19	18.4	13,200	638.8
17 September 1977	12.5	13.9	3,150	635.7
10 July 1978	21.5	19.8	15,700	632.8
16 July 1978	18.6	15.9	7,120	632.0

Note: Willow Beach Fish Hatchery is located at mile 12.

There was a fairly good agreement between the predicted and observed location of the interface (R = .83) (Table 5.5.3). However, at low discharge, the interface location was underestimated by equation (1). This could be improved if instantaneous discharge, corrected for transit time, was used in equation (1) rather than mean daily discharge. Additional investigation is being done to more precisely predict the location of the interface.

By equation (1), the interface would not extend above Willow Beach at the current minimum discharge (ca. 3000 ft.^{3}·sec^{-1}) from Hoover Dam or lake elevation (ca. 630-640 ft) in Lake Mohave. However, based on morphometry in the Black Canyon and minimum flows proposed for alternative B (2000 ft^3·sec^{-1}) and a reverse flow for alternative C (25,000 ft^3·sec^{-1}), the interface could extend well above Willow Beach. The 630 ft. and 640 ft. elevation contours extend to 1.5 miles below the dam and to Hoover Dam, respectively. Prolonged low discharge from Hoover Dam will probably not be sufficient to maintain the interface below Willow Beach, and, consequently, Lake Mohave water will extend into Black Canyon. With pump-back operation in alternative C, Lake Mohave water could be drawn as far up-stream as Hoover Dam. This will cause substantial fluctuations in the daily temperature regime in Black Canyon and the upper end of Lake Mohave.

On each power cycle, relatively cold water will be discharged from Hoover Dam and this will force Lake Mohave water down-lake, possibly well into Eldorado Canyon. However, at low discharge, and especially under pump-back

operation, relatively warm, epilimnetic water from Lake
Mohave will flow back into Black Canyon above Willow Beach.
Thus, the water temperature in this part of the river could
vary from a minimum of about 12.5°C, the current hypolimnion
temperature in Lake Mead, to a maximum of 20-25°C, the current
temperature of Lake Mohave surface water in the summer.

The Willow Beach Trout Hatchery relies almost entirely
on river-water to support their production of trout. Daily
fluctuations of temperature in the river-water would impair
the operation of the hatchery and, perhaps require that other
sources of water be provided to satisfy their requirements.
Similarly, the fluctuations in temperature would also affect
the trout and razorback sucker populations that inhabit the
river in Black Canyon and upper Lake Mohave. Although it is
unlikely that the temperature would increase to lethal levels,
these fish would certainly be subjected to some degree of
daily temperature stress that could alter their behavior,
distribution and perhaps population size.

There will also be increased fluctuations in river
temperature if Hoover Dam is operated from the upper gates.
Currently, the temperature of the discharge remains nearly
constant at 12.5°C throughout the year. However, this would
increase to 18-20°C by late summer if water is discharged from
the upper gates. The seasonal fluctuations in river tem-
perature would not alter the ecology of Black Canyon as
severely as the abrupt daily fluctuations. In fact, this
could actually benefit the invertebrate organisms and the
razorback sucker population in the canyon.

The Colorado River historically had a natural temperature cycle similar to that which now occurs in the surface waters of the reservoirs. The temperature of water discharged from the upper gates would be lower than surface waters, but the river would be returned to a natural cycle if these gates are used in the future. Aquatic invertebrates (e.g. mayflies) that historically occupied the river and relied on natural temperature cycles to trigger reproduction might return if the upper gates were used throughout the year (Miller et al. 1979). This, in turn would provide a substantial food resource that would benefit the fish populations. Although little is known about the life cycle of the razorback suckers in the river, it has been postulated that the cold and constant water temperature is detrimental to their reproductive success (Miller et al. 1979). If so, restoration of the river temperature to a natural cycle could directly benefit their population. It is not known how the rainbow trout would fare under such a temperature regime, but clearly they are capable of tolerating this range of temperature. Thus, if extreme daily fluctuations in temperature can be avoided, it appears that seasonal fluctuations will not adversely alter the ecology in Black Canyon below Hoover Dam.

The alterations in discharge required for each power modification will significantly influence the temperature and mixing patterns in Eldorado Canyon. In Lake Mohave, mixing created by entrainment of lake-water in Eldorado Canyon will be accelerated at high discharge from Hoover Dam. Also, if warmer water is discharged from Hoover Dam,

there will be less density difference between river-and lake-water which will further increase the rate of mixing. Evidence for this is provided from a limited series of temperature measurement made before, during and after a test release from Hoover Dam conducted by the U.S. Bureau of Reclamation in August, 1978.

Water temperature was 12.5°C below Hoover Dam on 16 July and 15 August, prior to and after the test release period. However, during the maximum discharge of 40,000 ft.^{3}·sec^{-1} on 8 August, the temperature below the dam increased to 13.5°C. At Eldorado Canyon, surface temperature was 25°C on 16 July and 26°C on 8 August, just prior to the maximum discharge. One week later, the surface temperature at Eldorado Canyon was 22.2°C which was nearly 4°C colder than on 8 August, 1978. This indicates that the high discharge of 40,000 ft.^{3}·sec^{-1} did cause considerable disruption of thermal stratification and accelerate mixing in Eldorado Canyon.

The accelerated mixing of river-and lake-water in this region will increase the availability of nutrients to phytoplankton. However, phytoplankton productivity will not change appreciably from the current levels. We could not detect any significant difference in productivity measurements that we made in Eldorado Canyon before, during and after the test release experiment in August. Even though this region of Lake Mohave is fairly productive, the instability created by fluctuations in discharge from Hoover Dam and continual flushing with river-water reduce the potential

for development of more serious phytoplankton blooms.

6.0 REFERENCES CITED

American Public Health Association. 1975. Standard methods
    for examination of water and wastewater. 13th edition.
    874 p.

Anderson, E.R. and D. W. Pritchard. 1951. Physical limnology
    of Lake Mead, Lake Mead Sedimentation Survey, U.S. Navy
    Electronic Laboratory, San Diego, California, Rept.
    No. 258, Oct. 3, 1951. 153 p.

Applegate, R.L. and J.W. Mullan. 1967. Zooplankton standing
    crops in a new and an old Ozark reservoir. Limnol.
    Oceanogr. 12: 529-599.

Bachman, R.W. and D.E. Canfield. 1979. Nutrient loading
    models and reservoirs. Amer. Soc. Limnol. Oceanogr.
    Wtr. Meet. Jan 2-5, 1979. Corpus Christi, Texas. (abstr.).

Baker, J.R., J.E. Deacon, T.A. Burke, S.S. Egdorf, L.J. Paulson,
    and R.W. Tew. 1977. Limnological Aspects of Lake Mead,
    Nevada-Arizona. Bur. of Reclamation Engineering and
    Research Center Rept. No. REC-ERC-77-9. 83 p.

Baker, J.R. and L.J. Paulson. 1978. The Las Vegas Wash
    density current in Lake Mead. Ariz.-Nev. Acad. Sci.
    22nd. Ann. Meet. April 14-15, 1978. Flagstaff, Arizona
    (abstr.).

Brooks, J.L. and S.I. Dodson. 1965. Predation, body size,
    and composition of plankton. Science. 150: 28-35.

Burke, T.A. 1977. The limnetic zooplankton community of
    Boulder Basin, Lake Mead in relation to the metalimnetic
    oxygen minimum. M.S. Thesis. Univ. Nev. Las Vegas.

Carter, J.C.H. 1974. Life cycles of three limnetic copepods
    in a beaver pond. J. Fish. Res. Board Can. 31: 421-434.

Deacon, J.E. 1975. Lake Mead Monitoring Program. Final
    Rept. to Clark County Wastewater Management Agency.
    297 p.

Deacon, J.E. 1976. Lake Mead Monitoring Program. Final
    Rept. to Clark County Sanitation District No. 1, Waste
    Treatment Physical Development Section. 182 p.

Deacon, J.E. 1977. Lake Mead Monitoring Program. Final
    Rept. to Clark County Sanitation District No. 1, Waste
    Treatment Physical Development Section. 55 p.

Deacon, J.E., L.J. Paulson and C.O. Minckley. 1970. Effects
    of Las Vegas Wash effluents upon bass and other gamefish
    reproduction and success. Univ. Nev. Las Vegas, D-J
    Project No. F 20-6. 68 p.

Deacon, J.E. and R.W. Tew. 1973. Interrelationship between chemical, physical and biological conditions of the waters of Las Vegas Bay of Lake Mead. Final Rept. to Las Vegas Valley Water District. 186 p.

Fogg, G.E., W.D.P. Stewart, P. Fay, and A.E. Walsby. 1973. The Bluegreen Algae. Academic Press. 459 p.

Gloss, S.P., L.M. Mayer and D.E. Kidd. 1979. Advective control of nutrient dynamics in the epilimnion of a large reservoir. Limnol. and Oceanogr. (manuscript).

Goldman, C.R. 1963. The measurement of primary productivity and limiting factors in freshwater with carbon-14 P. 103-113. In: M.S. Doty (ed.), Proc. Conf. Primary Productivity Measurement, Marine and Freshwater. A.E.C., Div. Tech. Inform. Rep. TID-7633.

Goldman, C.R. 1974. Eutrophication of Lake Tahoe emphasizing water quality. EPA - 660/3-74-034. U.S. Govt. Printing Office, Washington, D.C. 408 pp.

Goldman, C.R. 1976. A review of the limnology and water quality standards for Lake Mead. Ecological Research Associates. 101 p.

Golterman, H.L. 1969. Methods for Chemical Analysis of Fresh Waters. IBP Handbook #8 Blackwell Scientific Pub., Oxford and Edinburgh. 166 p.

Hall, D.J. 1964. An experimental approach to the dynamics of a natural population of Daphnia galeata mendotae. Ecology. 45:94-112.

Haney, J.F. 1973. An in situ examination of the grazing activities of natural zooplankton communities. Arch. Hydrobiol. 72:87-132.

Hoffman, D.W., P.R. Tramutt and F.C. Heller. 1967. Water Quality Study of Lake Mead. U.S. Bur. Rec. Chemical Engineering Rept. No. CHR-70. 155 p.

Hoffman, D.A., P.R. Tramutt and F.C. Heller. 1971. The effect of Las Vegas Wash effluent upon the water quality in Lake Mead. U.S. Bur. Rec Rept. No. REC-ERC-71-11. 25 p.

Hoffman, D.A. and A.R. Jonez. 1973. Lake Mead, a case history P. 220-233. In: W.C. Ackerman, G.F. White and E.B. Worthington (eds.) Man-Made Lakes: Their Problems and Environmental Effects. Geophysical Monograph Series No. 17. 847 p.

Hutchinson, G.E. 1957. A Treatise on Limnology: Volume 1 Geography, Physics and Chemistry. Wiley and Sons. 986 p.

Jonez, A. and R.C. Sumner. 1954. Lake Mead and Mohave
Iinvestigation. A comparative study of an established
reservoir as related to a newly created impoundment.
Nevada Fish and Game Division, Wildlife Restoration
Division. 186 p.

Kamphake, L.J., S.A. Hannah and J.M. Cohen. 1967. Automated
analysis for nitrate by hydrazine reduction. Water
Research. 1:205-216.

Lara, J.M. and J.I. Sanders. 1970. The 1963-64 Lake Mead
Survey. U.S. Bur. Rec. Rept. No. REC-OCE-70-21. 169 p.

Likens, G.E. 1975. Primary productivity of inland aquatic
ecosystems. p. 185-202. In: H. Lieth and R.H. Whittaken
(eds.) Primary Productivity of the Biosphere. Springer-
Verlag. 339 p.

Liddicoat, MJI., S. Tibbits and E.I. Butler. 1975. The
determination of ammonia in seawater. Limnol. and
Oceanogr. 20: 131-132.

Longwell, C.R. 1936. Geology of the Boulder Reservoir
floor. Geol. Soc. Amer. Bull. 47: 1393-1476.

Martin, D.B. and R.D. Arneson. 1978. Comparative limnology
of a deep-discharge reservoir and a surface-discharge
lake on the Madison River, Montana. Freshwat. Biol.
8:33-42.

McNatt, R. 1976. Effects of pumped storage operations on
aquatic environments of the Salt River Reservoirs,
Arizona. p. 62-66. In: J.F. Labounty (ed.). Third
Workshop in Ecology of Pumped Storage Research at Twin
Lakes, Colorado and Other Localities. U.S. Dept. of
Int. Bur. Rec. 107 p.

Mientke, C. and I. Mlynska. 1977. Balance of nutrients in
Kortowskie Lake waters during the experiment on its
lake restoration. Pol. Arch. Hydrobiol. 24: 49-59.

Miller, T.G., C.L. Keenan, J.R. Baker and L.J. Paulson. 1979.
Potential impacts of dredging Black Canyon. U.S. Bur.
Rec. Final Rept.

Minckley, W.L. and R.M. McNatt. 1976. Influence of pumped-
storage power generation on Central Arizona reservoirs.
U.S. Bur. Rec. Rept.# REC-ERC-76-18.

Moore, J.W. 1978. Some factors influencing the density and
birth rate of three subarctic rotifer populations. Arch.
Hydrobiol. 83:251-271.

Mullin, J.F. and J.P. Riley. 1955. The spectrophotometric
determination of nitrate in natural waters, with partic-
ular reference to seawater. Anal. Chem. Acta. 12:464-480.

Mullins, J.W., R.N. Snelling, D.D. Moden, and R.G. Seals. 1975. National Eutrophication Survey. Data Aquisition and Laborartory Analysis of Stream and Lake Samples. EPA-600/4-75-015. U.S. Env. Prot. Ag. Env. Man. and Supp. Lab. Las Vegas, Nev. 21 p.

Neel J.K. 1963. Limnology in North America (D.G. Frey ed.) University of Wisconsin Press, Madison. 734 p.

Paulson, L.J. andF. A. Espinosa. 1975. Fish trapping: a new method of evaluating fish species composition in limnetis areas of reservoirs. Calif. Fish and Game. 61:209-214.

Paulson, L.J. and J.R. Baker. 1978. Nutrient budgets for Lake Mead. Proceed. Ariz.-Nev. Acad. Sci. 22nd Ann. Meet., April 14-15, 1978, Flagstaff, Arizona.

Paulson, L.J. and J.R. Baker. 1979a. Possible causes for long-term changes in the nitrate budget and concentration in Lake Mead. Arizona-Nevada. Am. Soc. of Limnol. and Oceanogr. Wtr. Meet., Jan. 2-5, 1979, Corpus Christi, Texas. (abstr.).

Paulson. L.J. and J.R. Baker. 1979b. Factors regulating chlorophyll in Las Vegas Bay, Lake Mead. Ariz.-Nev. Acad. Sci. 23rd. Ann. Meet. April 13-14, 1979. Tempe Ariz. (abstr.).

Paulson, L.J., J.R. Baker and J.E.Deacon. 1979. Potential use of hydroelectric facilities for manipulating the fertility of Lake Mead. The Mitigation Symposium, Colorado State University, Fort Collins, Colorado. July 16-20, 1979. p. 296-300.

Paulson, L.J., J.E. Deacon and J.R. Baker. 1979. Potential use of hydroelectric facilities for managing the nutrient and trophic status of the reservoirs in the Colorado River. Proposal submitted to Office of Water Research and Technology, Washington. D.C.

Priscu, J.C., Jr. 1978. Primary productivity and related limnological factors in Lake Mohave (Colorado River). M.S. Thesis. Univ. of Nev. Las Vegas. 154 p.

Pennack, R.W. 1957. Species composition of limnetic zooplankton communities. Limnol. Oceanogr. 2:222-231.

Porter, K.G. 1973. Selective grazing and differential digenstion of algae by zooplankton. Nature. 244: 179-180.

Porter K.F. 1977. The plant-animal interface in freashwater ecosystems. Amer. Sci. 65:159-170.

Rigler, F.H. 1964. The phosphorus fractions and the turnover of inorganic phosphorus in different types of lakes. Limnol. Oceanogr. 9:511-518.

Sartoris, J.J. and D.A. Hoffman. 1971. Measurement of Currents in Lake Mead with the Deep Water Isotopic Current Analyzer (DWICA). U.S. Bur. Rec. Rept. # REC-ERC-71-38.

Saunder, G.W., F.B. Trama and R.W. Bachman. 1962. Evaluation of a Modified ^{14}C Technique for Shipboard Estimation of Photosynthesis in Large Lakes. Great Lakes Research Division Pub. #8. University of Michigan. 61 p.

Schindler, D.W. 1977. Evolution of phosphorus limitation in lakes. Science. 195:260-262.

Shapiro, J. 1960. The cause of the metalimnetic minimum of dissolved oxygen. Limnol. Oceangr. 5:216-227.

Sikorowa, A. 1977. Possibilities of protection against eutrophication of lakes using method of the removal of hypolimnion waters. Pol. Arch. Hydrobiol. 24:123-135.

Silvey, J.K.G. and J.A. Stanford. 1978. A historical overview of reservoir limnology in southwestern United States. P. 1-18. In: J. Cairns, E.F. Benfield, and J.R. Webster (eds.). Current Prospective on River-Reservoir Ecosystems. Proceed. Symposium of N. Amer. Benthological Society, Apr. 6-8, 1977, Roanoke, Virginia.

Smyly, W.J.P. 1961. The life-cycle of the freshwater copepod Cyclops leuckarti Claus in Esthwaite Water. J. Animal Ecol. 30:153-160.

Solorzano, L. 1969. Determination of ammonia in natural waters by the phenolhypochlorite method. Limnol. Oceanogr. 14:799-801.

Steeman-Nielsen, E. 1952. The use of radioactive carbon (C-14) for measuring organic production in the sea. J. Cons. Perm. Int. Explor. Mer. 18:117-140.

Strickland, J.D.H. and T.R. Parsons. 1968. A practical handbook of seawater analysis. Fish. Res. Bd. Can. Bull. 167. 311 p.

Stroud, R.H. and R.G. Martin. 1973. Influence of reservoir discharge location on the water quality, biology and sports fisheries of reservoirs and tailwater. P. 540-548 In: W.C. Ackermann, G.F. White and E B. Worthington (eds.) Man-Made Lakes: Their Problems and Environmental Effects. Geophysical Monograph Series #17. 847 p.

Syers, J.K., R.F. Harris and D.E. Armstrong. 1973. Phosphate chemistry in lake sediments. J. Env. Qual. 2:1-14.

Tappa, D.W. 1965. The dynamics of the association of six limnetic species of Daphnia in Aziscods Lake, Maine. Ecol. Monogr. 35:395-423.

U.S. Enviromental Protection Agency. 1978a. Report on Lake Mead, Clark County, Nevada, Mohave County, Arizona EPA Region IX. Working paper no. 808. National Environmental Research Centr. Las Vegas, Nevada and Pacific Northwest Environmental Research Laboratory, Corvallis, Oregon. 27 p.

U.S. Environmental Protection Agency. 1978b. Report on Lake Mohave, Mohave County, Arizona Clark County, Nevada EPA Region IX. Working Paper No 731. U.S. Environmental Protection Agency, National Eutrophication Survey. National Environmental Research Center, Las Vegas, Nevada, and Pacific Northwest Environmental Research Laboratory, Corvallis, Oregon. 16 p.

U.S. Department of Interior, Bureau of Reclamation. 1966. Reclamation Project Data, (supplement). 275 p.

U.S. Department of Interior, Bureau of Reclamation. 1977. Reclamation potentials within the Lake Mead National Recreation Area. 56 p.

U.S. Department of Interior, Bureau of Reclamation. 1978. Hoover power modifications, special report. 62 p.

Viner, A.B. 1975. Non-biological factors affecting phosphate recycling in the water of a tropical eutrophic lake. Verh. Int. Ver. Limnol. 19:2292-2313.

Vollenweider, R.A. 1968. Water management research. OECD Paris. DAS/CS1/68.27. 183 p.

Vollenweider, R.A. 1969. A Manual on Methods for Measuring Primary Production in Aquatic Environments. IBP Handbook #12. Blackwell Scientific Pub., Oxford and Edinburgh. 213 p.

Wetzel, R.G. 1975. Limnology. W.B. Saunders Co., Philadelphia, Pa. 743 p.

Wright, J.C. 1967. Effect of impoundments on productivity, water chemistry and heat budgets of rivers. P. 188-189. In: C.E. Lane (ed.) Reservoir Fishery Resources Symposium. Trans. Amer. Fish. Soc. Spec. Pub. N. 6. 569 p.

Wunderlich, W.O. and R.A. Elder. 1973. Mechanics of flow through man-made lakes. p. 300-310. In: W.C. Ackermann G.F. White and E.B. Worthington (eds.) Man-made Lakes: Their Problems and Environmental Effects. Geophysical Monograph Series No. 17. 847 p.

7.0 GLOSSARY OF TERMS

Advection
Transport of heat and material by current.

Biomass
Weight of living organic material per unit volume.

Chlorophyll
Green photosynthetic pigment of algae and other plants.

Conductivity
Measure of dissolved electrolytes in water.

Convergence
Region where an inflow enters and mixes with the reservoir.

Epilimnion
Warm, mixed, surface layer of the reservoir.

Entrainment
Fictionally induced parallel flow of reservoir water along
the boundary of an inflow.

Euphotic zone
Layer where light transmission is greater than 1% of
surface light.

Extinction coeffeicient (light)
Measure of rate of light attenuation with depth.

Flushing rate
see retention time

Heterocysts
Specialized cells of filamentous bluegreen algae where
fixation of atmospheric nitrogen occurs.

Heterograde (oxygen)
see metalimnetic minimum

Hypolimnion
Cold, non-turbulent, deep layer of a reservoir.

Interface
see convergence

Interflow
An inflow that flows at an intermediate depth in the
reservoir.

Isothermal
Term used to describe water layers with equal temperatures.

Lentic
Term used to describe standing water as in lakes, ponds and reservoirs.

Lotic
Term used to describe running water as in streams and river.

Macrophytes
Rooted vegetation that occurs along shorelines and in shallow littoral areas.

Metalimnion
Layer of gradual temperature change separating the epilimnion and hypolimnion.

Metalimnetic minimum (oxygen)
Depletion of oxygen in the metalimnion.

N: P ratio
Relative measure of the available nitrogen and phosphorus to algae.

Nitrification
Biologically mediated conversion of ammonia (NH_3) to nitrate (NO_3).

Nitrogen fixation
Process whereby bluegreen algae convert atmospheric nitrogen (N_2) to organic nitrogen.

Nutrient status
Index of fertility in lakes and reservoirs.

Overflow
An inflow that flows along the surface in a reservoir.

Periphyton
Group of algae attached to rocks and other natural substrates.

Phytoplankton
Group of free-floating algae.

Productivity (phytoplankton)
Rate of photosynthesis per unit volume per unit time.

Remineralization
Process of converting organic material to inorganic form.

Retention time (hydraulic)
Time required to replace entire water volume of a reservoir.

Retention (nutrient)
      Amount of nutrient input sedimented or otherwise stored
      in the reservoir.

Seston
      Biotic and abiotic material suspended in the water column.

Seiche
      Rhythmic oscillation of thermocline.

Thermocline
      Region of greatest change in vertical temperature
      structure of a lake or reservoir.

Trophic status
      Index of phytoplankton productivity in lakes and
      reservoirs.

Underflow
      An inflow that flows along the bottom in the reservoir.

Withdrawal layer
      Region of reservoir from where water is drawn for dis-
      charge.